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An Efficient Mathematical Model for Distribution System Reconfiguration Using AMPL

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ABSTRACT Distribution network is an essential part of electric power system, which however has higher power losses than transmission system. Distribution losses directly affect the operational cost of the system. Therefore, power loss reduction in distribution network is very important for distribution system users and connected customers. One of the commonly used ways for reducing losses is distribution system reconfiguration (DSR). In this process, configuration of distribution network changes by opening and closing sectional and tie switches in order to achieve the lowest level of power losses, while the network has to maintain its radial configuration and nodal voltage limits, and supply all connected loads. The DSR aiming loss reduction is a complex mixed-integer optimization problem with a quadratic term of power losses in the objective function and a set of linear and non-linear constraints. Accordingly, distribution network researchers have dedicated their efforts to developing efficient models and methodologies in order to find optimal solutions for loss reduction via DSR. In this paper, an efficient mathematical model for loss minimization in distribution network reconfiguration considering the system voltage profile is presented. The model can be solved by commercially available solvers. In the paper, the proposed model is applied to several test systems and real distribution networks showing its high efficiency and effectiveness for distribution systems reconfiguration.

INDEX TERMS Efficient mathematical model, electric power distribution systems, loss reduction, network reconfiguration, voltage profile.

I. INTRODUCTION

Active power loss minimization [1] is important for the distribution system efficiency and power quality. Changing distribution system configuration by opening and closing switches, while the network maintains its radial operation satisfying all loads is an effective way for loss reduction and voltage improvement [2], [3].

Distribution system reconfiguration (DSR) can be formulated as a large-scale combinatorial optimization problem with constraints that can often contain nonlinearities. The feasible search space in DSR is typically large, nonconvex, and hard to explore. Hence, determining good-quality solutions is always a challenging task. In order to cope with this issue, distribution system researchers have dedicated since a long time efforts to developing efficient models and methodologies for DSR.

DRS was first formulated as a mixed-integer non-linear optimization problem in 1975 using a branch-and-bound (B&B) algorithm [4]. Since then, several mathematical models have been presented, e.g. Civanlar *et al.* [5] formulated the DSR as a loss change estimation problem using DC load flow. However, the accuracy of the proposed model was questionable because it ignored the reactive current flows. In 1989,

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Shirmohammadi and Hong [6] improved this method to calculate network losses change by applying AC load flow in [6]. They introduced a heuristic algorithm to minimize the active losses using Lagrange multipliers [6]. In order to increase precision and decrease calculation time, Baran and Wu [7] formulated the resistive losses in quadratic terms of active and reactive powers using fast radial power flow. This was, however still time consuming because of the step by step branch exchange (BE) strategy. One year later, Castro *et al.* [8] presented a new estimated model for the DSR problem, in which switching proposals with negative loss change (those reduced the power losses after reconfiguration) are selected and ones with positive change in losses are discarded in an iterative process. The proposed model was robust, efficient and very simple, because only the voltage drops at the extremes of the tie lines and the amount of transferred load were used for evaluation of the loss change. However, this formulation cannot be applied to large-scale reconfiguration problems.

In 1992, Nara *et al.* [9] presented a binary integer programing formulation for the DSR by representing power losses as quadratic terms of load and branch currents using genetic algorithm (GA). Nevertheless, implementation of this model on large-size distribution networks is very difficult.

Later, Chang and Kuo [10] used simplified load flow equations for the formulation of the DSR problem using simulated annealing (SA). Although the proposed model reduces the processing time of loss minimization, it can decrease the quality of solutions in combinatorial DSR problems.

Lee *et al.* [11] presented a linear mixed-integer model for loss minimization in DSR using linearized load flow equations. Performance indices as ratio of power losses to rated current of each branch were defined for possible switching combinations. In this process, a switching proposal with the lowest performance index is selected for network reconfiguration. Nonetheless, the effectiveness and efficiency of proposed formulation was verified only for small test systems.

In 1995, Peponis *et al.* [12] presented a new model for minimization of energy losses via network reconfiguration and optimal installation of shunt capacitors under different load models. The proposed loss estimation-based framework is an efficient and simple reconfiguration model that can find optimal switching combination using BE. The results show that method of load formulation affects the solutions of DSR and capacitor placement problem significantly. However, BE is a time-consuming heuristic method for network reconfiguration.

Sarma and Rao [13] introduced a new model for network reconfiguration, allocating distribution feeders to different circuits, by representing network losses in terms of circuits' currents. The status of each bus was defined by binary numbers, in which number 1 indicates connection between bus and related circuit. However, presenting the losses in this form is not easy for medium and large-sized distribution systems.

In order to overcome the size restrictions of previously described reconfiguration models, Sárf *et al.* [14] presented a network partitioning theory to solve the DSR problem in 1996. In this method, the distribution network was divided into groups of buses and the power losses between these groups were minimized. The performance of proposed model was tested on a small-sized distribution network.

Three years later, a discrete ascent optimal programming (DAOP) based model for distribution network reconfiguration was proposed in [15]. In DAOP, the optimal configurations with the smallest discrete increase in total losses are selected by picking up and adding the loads as incremental steps. However, this method takes more computational time than other reconfiguration techniques.

In 2001, Kashem *et al.* [16] presented a geometrical approach to maximize losses reduction in DSR. In this method, a circle is allocated to each loop of the network and a loop with maximum influence on loss reduction is selected according to its radius. Then possible branch exchanges are investigated in selected loop by comparing the size of the circle for every branch exchange. If the power losses are reduced due to a branch exchange, the size of the circle diminishes and hence the circle with smallest radius gives configuration with maximum losses reduction. The geometrical method can reduce the computing time, but determination of appropriate circles is difficult in large distribution systems.

One year later, Arun and Aravindhababu [17] proposed an efficient SA for network reconfiguration, aiming losses minimization. Although the proposed algorithm provided better solutions for DSR compared to SA, its implementation on large size distribution networks is hard.

In 2003, Su and Lee [18] introduced a mixed-integer hybrid differential evolution (MIHDE) algorithm for DSR formulation. The model was combination of hybrid differential evolution (HDE) and integer programing. It was proved that MIHDE has less computational burden than SA, but its application to large-scale DSR problems is not easy.

Two years later, Schmidt *et al.* [19] introduced a new approach based on Newton power flow method to model the DSR problem. Increase in power loss of each branch was estimated by linear and quadratic terms of branch current using gradient vector and the Hessian matrix. Although, the approximations used in loss formulation improved the speed of the method, they may prevent the algorithm to find accurate solutions in large-scale distribution systems.

In order to reduce the number of power flows and subsequent computing time of reconfiguration models, in 2006, Gomes *et al.* [20] formulated the DSR as an optimal power flow (OPF) problem using sensitivity analysis. Using this formulation, Raju and Bijwe [21] presented active power losses as linear terms of loss sensitivity to the branch impedances in 2008. The candidate branches for network reconfiguration were ranked based on their loss sensitivity. In the first stage, all switches were considered to be closed and the candidate ones with minimum loss increase were opened one-by-one. In the second stage, the best switching proposals were selected by BE method.

One year later, Khodr *et al.* [22] modeled the DSR using Benders decomposition (BD) in general algebraic modeling system (GAMS) [23]. First, possible radial topologies for network reconfiguration were determined by minimizing quadratic objective function of losses considering line flow limits. Then, OPF was run to assess the feasibility of the obtained solutions. Although the computational results presented by [20], [21], and [22] demonstrated the effectiveness and robustness of the proposed methodologies, the efficiency of the proposed models degrades with the increase of non-linear terms.

In 2010, Wu *et al.* [24] mentioned that lower power losses and better load balancing can be achieved by considering distributed generation (DG) in DSR. In 2011, for the first time, the harmony search algorithm (HSA) was employed to solve the DSR problem by [25]. The HSA is a new metaheuristic algorithm with less parameters and easier implementation compared to SA and GA. However, determination of the penalty coefficients of fitness function is relatively hard in HSA.

One year later, Lavorato *et al.* [26] presented a new formulation for the DSR problem with a new radiality constraint. The main contribution was to find optimal radial topologies without any transfer nodes (buses without generation and demand) at ends of them. In other words, transfer nodes should be connected to the network via at least two branches or must be isolated. However, this kind of modeling just increases computational time without other gains.

Jabr *et al.* [27] formulated the DSR problem using mixed-integer non-linear programming (MINLP). The network losses were represented in quadratic and mutual terms of nodal voltage magnitudes. The results showed that solutions obtained by MINLP are the same with those obtained by mixed-integer linear programing (MILP). Nevertheless, writing the nonlinear power flow equations in terms of quadratic constraints requires additional mathematical efforts.

Later, Taylor and Hover [28] modeled DSR by quadratic programming (QP) and quadratically constrained programming (QCP) as a convex problem. In QCP based model, an inequality constraint describing the relationship of maximum complex power with its quadratic terms (active and reactive powers) was added to the problem constraints. The results indicated that performances of QP and QCP are better than the models formulated by BD.

Llorens-Iborra *et al.* [29] presented a MILP model that approximates power losses by a piecewise linear function. Although, the proposed linear model can be easily solved by commercial optimization solvers, the approximations used may degrade its performance when solving highly non-linear combinatory DSR problems.

In 2013, Ferdavani *et al.* [30] improved model of [21] by using neighbour-chain updating process (NCUP) rather than BE. It means, in the second stage, each open switch of the proposed topology with its best neighbourhood switches were updated by NCUP. The results revealed notable improvement in solutions of [21].

Two years later, Ahmadi and Martí [31] modeled the radiality constraint of the DSR as a spanning tree optimization problem using graph theory. The minimum spanning tree problem was solved by optimizing weighted sum of the edge connecting vertexes of original graph to those of its dual graph. This formulation decreased the reconfiguration time of planar networks, it cannot however be applied to non-planar distribution systems. Planar networks are systems that have planar graphs, i.e. their graphs can be drawn in a way that no edges cross each other. [32] and [33] presented simple linear current flow equations to minimize losses by approximating the quadratic terms of real and reactive current flows in the objective function with linear terms.

Hijazi and Thiébaux [34] developed a binary convex model for the DSR problem, in which binary variables related to status of switches (on-off) were efficiently embedded in the problem formulation. The simulation results confirmed that the proposed approach was faster than models presented by [27] and [28] for large-scale distribution systems. Nevertheless, the computational burden for medium-size distribution networks was higher than QCP-based models [28].

In 2016, Haghighat and Zeng [35] proposed a robust MILP model for reconfiguration of distribution systems under load variations and uncertainty. However, piecewise linear approximations used in the MILP model can reduce accuracy of the solutions. Moreover, high complexity of applied two-stage reconfiguration algorithm has decreased possibility of model implementation in real reconfiguration applications.

On year later, Khorshid-Ghazani *et al.* [36] included protection concepts in DSR formulation. In the proposed approach, operational constraints of protective devices were considered in the objective function as penalty terms. The results declared that DSR without considering coordination among over-current relays, reclosers, and fuses cannot be realistic.

In 2018, Mishr and Swarup [37] formulated DSR for smart distribution networks using multi agent systems (MAS). The optimal topology was identified based on interaction among agents of generator (substations and DG units), demand (load points), and bus (nodes) through their communication. The proposed approach can maximize the network serviceability when small load changes occur during continuous monitoring of demand conditions.

Recently, Jahani *et al.* [38] modeled DSR problem including demand response (DR) in order to enhance the network reliability and reduce power losses. The results showed that the reliability of system is improved via DSR and DR program. Later, Yang *et al.* [39] formulated distribution network reconfiguration in presence of power flow controllers. It was shown that flexible DC device (FDD) improves DSR solutions by adjusting line power flows in coordination with switching scenarios.

More recently, Azizivahed *et al.* [40] presented dynamic DSR problem in presence of renewable energy resources and energy storage systems (EESs). The proposed strategy is useful to find the appropriate switching operations, the best schedules for charging and discharging of batteries, and optimal outputs of generators. However, the solutions were obtained from the distribution companies (DISCOs) point of view. In order to reduce the computational time of multi-objective DSR problems, Wang *et al.* [41] proposed a chaos disturbed beetle antennae search (CDBAS) algorithm. Grey target decision-making technology was used to adopt CDBAS for multi-objective frameworks. The results confirmed better performance of the proposed methodology compared to other reconfiguration methods for multi-objective DSR applications.

This paper presents an efficient mathematical formulation for DSR that is simple to implement and is characterized by high precision and short computational time. The robustness and effectiveness of the model is tested in different types of distribution systems using CPLEX in AMPL. In contrast to the previous methods that were tested in specific networks, the proposed formulation proves efficient and effective for reconfiguration of all kinds of distribution systems (planar or non-planar) with different sizes (from small to very large distribution networks), several substation buses, and many transfer nodes. Accordingly, the objectives of current study are:

1) To present efficient formulation for DSR that can be implemented easily by available optimization tools and classic methods.
2) To introduce an exact mathematical model for network reconfiguration without any estimation.
3) To reduce processing time of DSR calculations.
4) To guarantee connectivity of proposed radial topologies.

In addition, the article aims to serve as a good reference for future reconfiguration works because it includes many different kinds of test systems that are used to compare the proposed framework regarding losses, voltage profile, and execution times. In summary, the paper presents an efficient DSR model that satisfies radiality constraints for every distribution network with the following key characteristics:

- Its formulation is simple and can be solved by linear commercial solvers.
- It requires short computing times without introducing approximations, linearizations, decompositions, and complexities.
- The model is general and applicable for reconfiguration of both planar and non-planar distribution networks.
- It is implemented in several test systems exhibiting a superior performance. The different kinds of distribution networks can be used as test cases for future studies regarding DSR.

II. MATHEMATICAL FORMULATION

The problem is the determination of the switch status of branches (open or close) to minimize network losses (P_{Loss}) under technical constraints concerning bus voltage limits. Assuming the network is represented as pairs of receiving

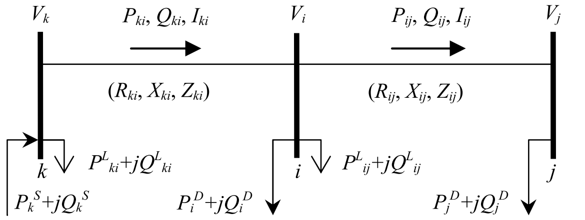

FIGURE 1. Basic representation of the network.

and sending buses connected by distribution lines, as shown in Fig. 1, the DSR problem for balanced distribution networks can be formulated by (1) to (10).

$$Min\ P_{Loss} = \sum_{ij\in\Omega^l} P^L_{ij} \tag{1}$$

subject to:

$$P^S_i + \sum_{k=1}^{n} P_{ki} = \sum_{j=1}^{n} P_{ij} + \sum_{j=1}^{n} P^L_{ij} + P^D_i \tag{2}$$

$$Q^s_i + \sum_{k=1}^{n} Q_{ki} = \sum_{j=1}^{n} Q_{ij} + \sum_{j=1}^{n} Q^L_{ij} + Q^D_i \tag{3}$$

$$\begin{aligned}\left|V_j\right|^2 - |V_i|^2 = {} & 2\left(R_{ij}P_{ij} + X_{ij}Q_{ij}\right) \\ & - \left(R^2_{ij} + X^2_{ij}\right)\left|I_{ij}\right|^2 + b_{ij}\end{aligned} \tag{4}$$

$$\left|S_{ij}\right|^2 = P^2_{ij} + Q^2_{ij} \tag{5}$$

$$\left|S_{ij}\right| = \left|V_j\right|\left|I_{ij}\right| \tag{6}$$

$$\sum_{ij\in\Omega^l} y_{ij} = n - 1 \tag{7}$$

$$V_{\min} \le |V_i| \le V_{\max} \tag{8}$$

$$0 \le \left|I_{ij}\right| \le I^{\max}_{ij} y_{ij} \tag{9}$$

$$-M\left(1 - y_{ij}\right) \le b_{ij} \le M\left(1 - y_{ij}\right) \tag{10}$$

Ω^l is the set of branches and n is the number of buses (nodes). P^L_{ij} and Q^L_{ij} are the active and reactive power losses in branch ij. S_{ij}, P_{ij}, and Q_{ij}, are complex, active, and reactive power flows on branch ij, respectively. $|V_i|$, V_{min}, and V_{max} are the voltage magnitude at bus i, and its minimum and maximum limits. P^S_i, Q^S_i, P^D_i, and Q^D_i are active and reactive powers of substation and load demands at bus i, respectively. It should be noted that $|I_{ij}|$ and I^{max}_{ij} are current flow magnitude and maximum current of branch ij. R_{ij} and X_{ij} are the resistance and reactance of branch ij, respectively. Finally, b_{ij} is a variable for representing the Kirchhoff voltage law (KVL) in the loop formed by branch ij and y_{ij} is a binary variable of the switch status of branch ij (0 for open and 1 for closed switches).

Equations (2) and (3) express nodal active and reactive power balances (Kirchhoff's current law, KCL). Equation (4) describes that net summation of voltage drops of all branches in a planar loop, which has to be equal to zero (KVL). In this equation, b_{ij} will be zero, when switch of branch ij is closed (KVL must be established) and will be a real number for open branches (KVL is not necessary). Equation (5) represents the relationship between complex power of each branch and its active and reactive components. Also, (6) represents the complex power in terms of nodal voltages and branch currents. Equation (7) indicates radiality constraint. Accordingly, the total number of branches under operation (total number of closed switches) has to be equal to the total number of buses minus one (according to graph theory). Constraints (8) and (9) show voltage and current limits, respectively. It should be mentioned that (8) provides an acceptable voltage level for network buses in order to compensate voltage drop. (10) makes sure that the value of b_{ij} will be zero, if the switch of branch ij is closed ($y_{ij} = 1$) and a real number between M and $-M$, when the corresponding branch is disconnected ($y_{ij} = 0$). In order to determine the value of M, let's consider that the switch of branch ij is open. From (9), it is obtained that $|I_{ij}|$ will be zero because of $y_{ij} = 0$, and therefore $P_{ij} = Q_{ij} = 0$ due to (5) and (6). Thus, the maximum value of M is $V_{max}^2 - V_{min}^2$ because $b_{ij} = |V_j|^2 - |V_i|^2$ (4) and the maximum difference between lower and upper voltage limits (8).

A. PROPOSED MIXED-INTEGER NONE-LINEAR PROGRAMMING (MINLP) MODEL

The model described by (1) to (10) can be used for reconfiguration of distribution systems with one substation bus. By replacing $P_{ij}^L = R_{ij}|I_{ij}|^2$ and $Q_{ij}^L = X_{ij}|I_{ij}|^2$ in (1) to (3) and equation (6) in (5), it can be seen that all equations are described in terms of real variables $|I_{ij}|^2$, $|V_i|^2$, and $|V_j|^2$ and binary variables y_{ij}, except of (8) and (9).

In order to extend the model to include distribution networks with several substation buses following formulation is presented.

$$\text{Min}\, P_{Loss} = \sum_{ij \in \Omega^l} R_{ij} \left|I_{ij}\right|^2 \tag{11}$$

subject to:

$$P_i^s + \sum_{k=1}^{n} P_{ki} = \sum_{j=1}^{n} P_{ij} + \sum_{j=1}^{n} R_{ij} \left|I_{ij}\right|^2 + P_i^D \tag{12}$$

$$Q_i^S + \sum_{k=1}^{n} Q_{ki} = \sum_{j=1}^{n} Q_{ij} + \sum_{j=1}^{n} X_{ij} \left|I_{ij}\right|^2 + Q_i^D \tag{13}$$

$$\begin{aligned}\left|V_j\right|^2 - |V_i|^2 &= 2\left(R_{ij}P_{ij} + X_{ij}Q_{ij}\right)\\ &\quad - \left|Z_{ij}\right|^2 \left|I_{ij}\right|^2 + b_{ij}\end{aligned} \tag{14}$$

$$\left|V_j\right|^2 \left|I_{ij}\right|^2 = P_{ij}^2 + Q_{ij}^2 \tag{15}$$

$$\sum_{ij \in \Omega'} y_{ij} = n - n_s \tag{16}$$

$$V_{\min}^2 \leq |V_i|^2 \leq V_{\max}^2 \tag{17}$$

$$0 \leq \left|I_{ij}\right|^2 \leq \left(I_{ij}^{\max}\right)^2 y_{ij} \tag{18}$$

$$\left|b_{ij}\right| \leq M\left(1 - y_{ij}\right) \tag{19}$$

In above equations, n_s and $|Z_{ij}|$ are the number of substation buses and the impedance magnitude of branch ij, respectively.

B. PROPOSED MIXED-INTEGER CONIC PROGRAMMING MODEL

The solution of the MINLP model presented in Section II by classical optimization tools is not always straightforward, because of the non-convexity in problem formulation (15). Furthermore, quadratic terms of the problem variables (e.g. branch currents and nodal voltages) prevent optimization of the model by linear commercial solvers. In addition, radiality constraint (16) does not include transfer nodes, while real distribution networks often contain buses without substation or demand (transfer nodes). Moreover, additional constraints can be included in the problem formulation in order to increase the accuracy of the model and reduce its execution time. Therefore, in order to create a convex model that can be easily solved by mathematical and metaheuristic techniques and optimization tools (even linear commercial solvers), the following mixed-integer conic programming (MICP) model is proposed. In this model, $I_{ij}^{sqr} = |I_{ij}|^2$, $V_i^{sqr} = |V_i|^2$, and $V_j^{sqr} = |V_j|^2$.

$$\text{Min}\, P_{Loss} = \sum_{ij \in \Omega'} R_{ij} I_{ij}^{sqr} \tag{20}$$

subject to:

$$P_i^S + \sum_{k=1}^{n} P_{ki} = \sum_{j=1}^{n} P_{ij} + \sum_{j=1}^{n} R_{ij} I_{ij}^{sqr} + P_i^D \tag{21}$$

$$Q_i^S + \sum_{k=1}^{n} Q_{ki} = \sum_{j=1}^{n} Q_{ij} + \sum_{j=1}^{n} X_{ij} I_{ij}^{sqr} + Q_i^D \tag{22}$$

$$\begin{aligned}V_j^{sqr} - V_i^{sqr} &= 2\left(R_{ij}P_{ij} + X_{ij}Q_{ij}\right)\\ &\quad - \left|Z_{ij}\right|^2 I_{ij}^{sqr} + b_{ij}\end{aligned} \tag{23}$$

$$y_{ij} = \beta_{ij} + \beta_{ji} \tag{24}$$

$$\sum_{j=1}^{n} \beta_{ij} = 1 \tag{25}$$

$$\beta_{ij} = 0 \quad \forall i \in \Omega^s, \forall ij \in \Omega^l \tag{26}$$

$$\beta_{ji} = 0 \quad \forall j \in \Omega^s, \forall ij \in \Omega^l \tag{27}$$

$$P_{ij}^{\max} = V_{\max} I_{ij}^{\max} \tag{28}$$

$$Q_{ij}^{\max} = V_{\max} I_{ij}^{\max} \tag{29}$$

$$V_j^{sqr} I_{ij}^{sqr} \geq P_{ij}^2 + Q_{ij}^2 \tag{30}$$

$$V_{\min}^2 \leq V_i^{sqr} \leq V_{\max}^2 \tag{31}$$

$$0 \leq I_{ij}^{sqr} \leq \left(I_{ij}^{\max}\right)^2 y_{ij} \tag{32}$$

$$\left|b_{ij}\right| \leq \left(V_{\max}^2 - V_{\min}^2\right)\left(1 - y_{ij}\right) \tag{33}$$

$$\left|P_{ij}\right| \leq P_{ij}^{\max} y_{ij} \tag{34}$$

$$\left|Q_{ij}\right| \leq Q_{ij}^{\max} y_{ij} \tag{35}$$

Ω^s is the set of substation buses. P_{ij}^{max} and Q_{ij}^{max} are the maximum active and reactive powers of branch ij, respectively and β_{ij} is the binary variable to show direction of power flow in branch ij.

Equations (24) to (27) impose the radiality constraint on DSR problem. This set of equations helps to find optimal radial topologies in every distribution system (both small and large networks, with one or several substations, and with or without transfer nodes) much faster than (16). These equations also maintain the connectivity of the network during reconfiguration better than (16) (i.e., none of buses is isolated from the network during optimization process). Also, (34) and (35) show that active and reactive power flows of branches should be limited by their maximum values. Although equations (31) and (32) provide these conditions, constraints (34) and (35) improve computing time and quality of solutions.

III. SOLUTION METHOD

The proposed mathematical formulation is a MINLP problem including binary variables y_{ij} and β_{ij}, real variables P_{ij}, Q_{ij}, P_i^S, Q_i^S, I_{ij}^{sqr}, V_i^{sqr}, and b_{ij}, a linear objective function (20), linear constraints (21)–(29), (31)–(35), and convex nonlinear restriction (30). The problem can be solved using analytical methods, heuristic techniques, and metaheuristic algorithms. It should be noted that heuristics and metaheuristics cannot guarantee the global optimum.

Classic methods, based on mathematical programming, are widely used to solve the DSR problem. Linear mathematical problems with a linear objective function and constraints can be solved by linear programing. Linear programming is particularly important, because a wide variety of problems can be modeled as linear, and because there are fast and reliable methods for solving linear problems even with thousands of variables and constraints. The ideas of linear programming are also important for analyzing and solving not linear mathematical programming problems. Nonlinear programing is used for optimization of nonlinear objective functions, subject to nonlinear constraints. Solving such a problem is harder, though not impossible. Integer programming is used to solve objective and constraint functions of real, binary and integer variables. Solving the problem by integer programming is much harder than linear and nonlinear programming. For this purpose, AMPL as an algebraic modeling language has been designed for mathematical programming. The AMPL is a powerful optimization tool that can be used efficiently to solve the proposed MICP problem. This problem can be optimized by linear or non-liner solvers of AMPL. However, linear solvers can are more efficient than nonlinear ones, because of the linear nature of the problem. One of the most efficient linear solvers of AMPL is CPLEX. Therefore, the proposed distribution network reconfiguration problem is solved by CPLEX in AMPL. In order to highlight the model accuracy and verify the results of AMPL, decimal codification GA (DCGA) presented in [42] was adopted for solving proposed DSR problem in addition to CPLEX.

IV. NUMERICAL RESULTS AND CASE STUDIES

The proposed model was applied to several test systems using CPLEX and the results were compared with DCGA and solutions obtained by other formulations and methodologies, such as heuristic methods [30], [43]–[50], simulated annealing (SA) [51]–[54], tabu search (TS) [55], [56], modified TS (MTS) [57], genetic algorithms (GAs) [24], [52], [53], [58]–[73] (e.g. refined GA (RGA) [61], fuzzy GA (FGA) [62], binary GA (BGA) [63], GA based on Matroid theory (GAMT) [66], and SOReco [67]), particle swarm optimization (PSO) [74]–[79], plant growth simulation (PGS) [80], [81], ant colony optimization (ACO) [24], [52], [53], [82]–[86], harmony search algorithm (HSA) [25], [53], and honey bee mating optimization (HBMO) [53], [79], [87], [88]. In order to provide an accurate and broad comparison between performance of the proposed model and that of most existing reconfiguration alternatives, the results are discussed based on static load values. To confirm effectiveness of the proposed methodology for real applications, the reconfiguration results for variable load amounts have been given in Appendix. The results of Appendix show high efficiency of the proposed model for reconfiguration of practical distribution networks under load variations.

A. CASE 1: 7-BUS DISTRIBUTION NETWORK

Figure 2 shows the test system with six branches (closed switches) and one loop (tie line). All data related to this system are given in [89]. The base power is 1 MVA and the nominal voltage is 12.66 kV. The maximum current capacity (I_{ij}^{max}) of each branch was considered to be 500 A.

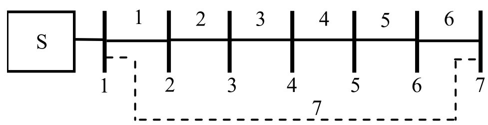

FIGURE 2. The 7-bus test system [89].

The results of the proposed model, such as open switches (branches), active power losses (kW), and computing time (s) are listed in Table 1. Voltage profiles of the system before and after reconfiguration are illustrated in Fig. 3. In addition, voltage profiles after reconfiguration by the optimal switching operation by the proposed model and of the reconfiguration proposed by [89] are shown in Fig. 4. Moreover, the optimization process of power losses in GA is represented by Fig. 5. This figure confirms the accuracy of solutions found by proposed model.

As shown in Table 1, the active power losses obtained by the proposed model are much lower than the ones obtained by the method of [89].

From Fig. 3, it can be seen that bus voltages are increased by reconfiguration, because the voltage drop on distribution lines is decreased. It should be noted that the minimum voltage at bus 5 is increased from 0.9946 p.u. to 0.9981 p.u. after reconfiguration.

TABLE 1. Numerical results for case 1.

Model	Open Switches	Power Losses (kW)		Time (s)
		Before Reconfiguration	After Reconfiguration	
[89]	4	1.44	1.2	–
DCGA	5	1.44	0.82	0.19
Proposed	5	1.44	0.82	0.12

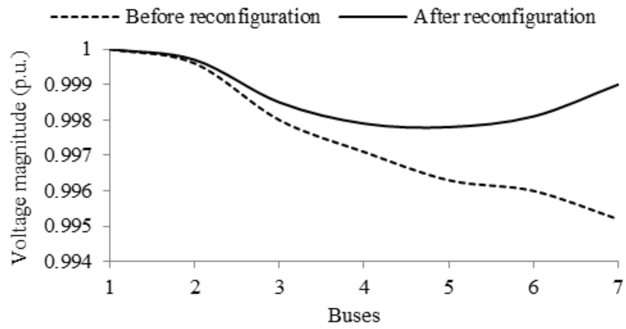

FIGURE 3. The voltage profile before and after reconfiguration of the 7-bus test system by the proposed model.

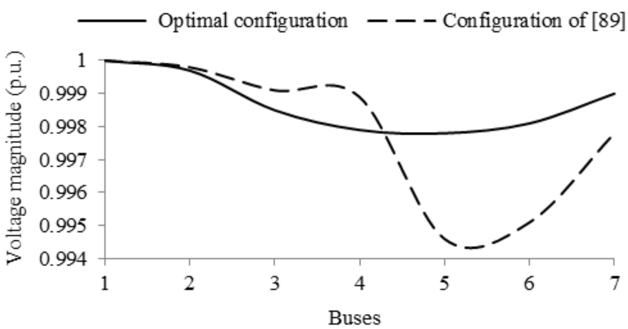

FIGURE 4. The voltage profile after reconfiguration of the 7-bus test system compared to model of [89].

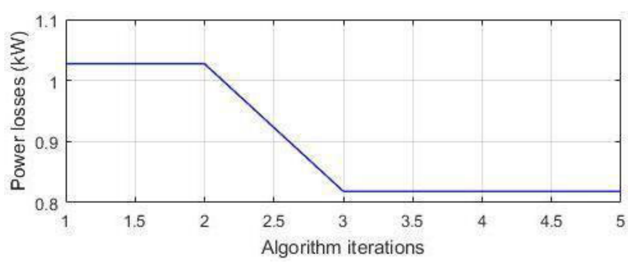

FIGURE 5. Power losses versus GA iterations for case 1.

As shown in Fig. 4, the MICP model improves significantly the voltage profile compared to the model of [89]. Figure 5 demonstrates that DCGA can find the optimal switching proposal after three iterations.

B. CASE 2: 12-BUS DISTRIBUTION NETWORK

This model represents an actual system, part of the distribution network of Baghdad city in Iraq (AL-Mansoor No.11). Its single line diagram is shown in Fig. 6. The feeder is connected to the AL-Mansoor substation, which has a nominal (base) voltage of 11.1 kV and a capacity of 2250 kVA. The relevant data have been given in [90]. The maximum current capacity of each branch is assumed to be 500 A. There are two tie line switches and 13 branches in this network. The results obtained by the proposed method are provided in Table 2. The voltage profiles before reconfiguration (base case) and after reconfiguration by the proposed optimal switching method are shown in Fig. 7 and the respective results obtained by [90] are depicted in Fig. 8. The minimization process of power losses is given in Fig. 9.

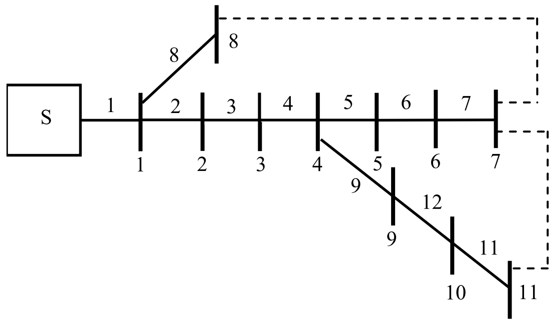

FIGURE 6. Distribution network of AL-Mansoor No.11.

TABLE 2. Numerical results for case 2.

Model	Open Switches	Power Losses (kW)		Time (s)
		Before Reconfiguration	After Reconfiguration	
[90]	12,13	3.55	2.55	0.4
DCGA	3,9	3.55	1.31	0.24
Proposed	3,9	3.55	1.31	0.08

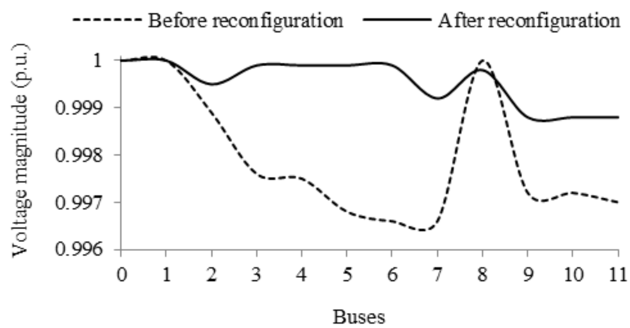

FIGURE 7. The voltage profile before and after reconfiguration of the 12-bus test system by the proposed model.

From Table 2, it can be seen that the proposed model and DCGA were able to reduce active power losses by 47.84% compared to the model used in [90]. Also, the proposed reconfiguration framework could reach the optimal solution much faster than model presented in [90]. Figure 9 shows that GA approaches the optimal configuration after three iterations.

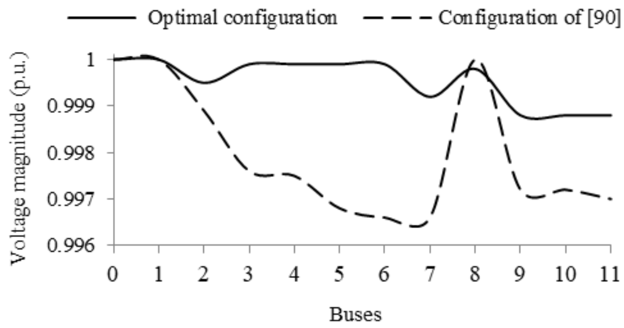

FIGURE 8. The voltage profile after reconfiguration of the 12-bus test system by the proposed model compared to the model of [90].

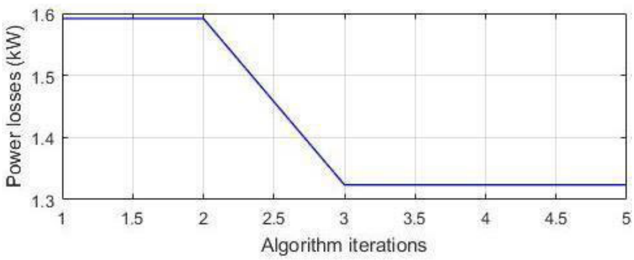

FIGURE 9. Power losses versus GA iterations for case 2.

Moreover, Fig. 7 and 8 show that the system voltage is improved considerably after reconfiguration by the proposed model compared to the base case and the model presented in [90] (e.g. the minimum voltage of the system at bus 7 has been increased from 0.9966 p.u. to 0.9992 p.u. after reconfiguration). Accordingly, it can be concluded that the proposed MICP model is more efficient than approach presented in [90] and faster than GA.

C. CASE 3: 16-BUS DISTRIBUTION NETWORK

A three-feeder 23 kV distribution system including 13 sectional switches (branches) and three tie lines is shown in Fig. 10.

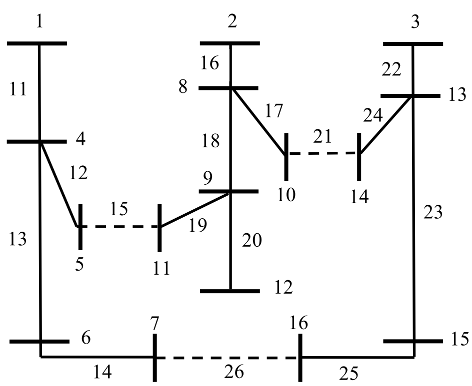

FIGURE 10. The 16-bus test system [91].

All data, such as resistance and reactance of branches, and nodal active and reactive demands are reported in [91].

TABLE 3. Numerical results after reconfiguration for case 3.

Model	Open Switches	Power Losses (kW)	Time (s)
[5]	15,17,26	488.46	–
[8]	15,17,26	485.9	–
[14]	15,17,26	483.88	–
[32]	17,19,26	468.3	–
[31]	17,19,26	468.3	0.16
[30]	17,19,26	466.14	–
[44]	17,19,26	466.13	–
[20]	17,19,26	466.13	–
[45]	17,19,26	466.13	–
[70]	17,19,26	466.13	0.45
[68]	17,19,26	466.13	0.27
[69]	17,19,26	466.12	2.027
[76]	17,19,26	466.12	0.156
[56]	17,19,26	466.1	–
[54]	17,19,26	466.1	–
[55]	17,19,26	466.1	–
[57]	17,19,26	466.1	–
[43]	17,19,26	466.1	8
[51]	17,19,26	466.1	7.5
[10]	17,19,26	466.1	6
[91]	17,19,26	466.1	4.5
GA [52]	17,19,26	466.1	2.32
SA [52]	17,19,26	466.1	2.07
ACO [52],[82]	17,19,26	466.1	1.81
[66]	17,19,26	466.1	1.35
DCGA	17,19,26	466.1	1.33
[67]	17,19,26	466.1	0.212
Proposed	17,19,26	466.1	0.12

The base power is 10 MVA and the maximum currents of branches 11, 16, and 18 are considered 500 A, 500 A, and 300 A, respectively, while those of all other branches 250 A. The proposed model was applied to the 16-bus distribution network and results in comparison with alternative methods are presented in Table 3. It should be noted that the computing time of some alternative methods has not been reported. Therefore, the models are ranked in related tables, according to power losses, then computational time, and afterward date of their publications.

The active power losses of the original network (base case) are 511.4 kW. The models proposed in [5], [8], and [14] do not provide the optimal switching scenario (17,19,26), in contrast to other approaches and the proposed model. It is shown that the proposed strategy provides optimal solution in shorter computing time compared to other reconfiguration methodologies. The profiles of bus voltages before and after reconfiguration using the proposed optimal switching operation (17,19,26) and the configurations proposed

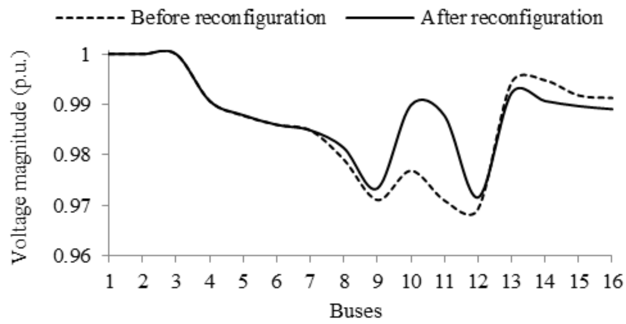

FIGURE 11. The voltage profile before and after reconfiguration of the 16-bus test system by the proposed model.

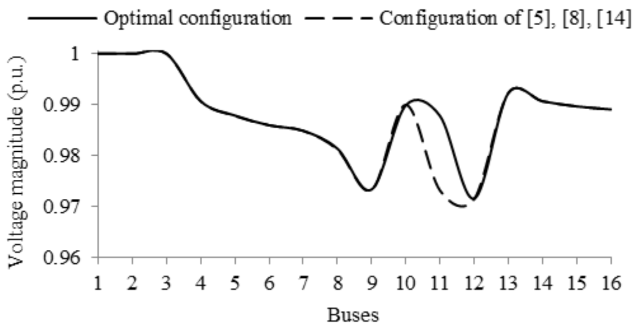

FIGURE 12. The voltage profile after reconfiguration of the 16-bus test system by the proposed model compared to the models of [5], [8], and [14].

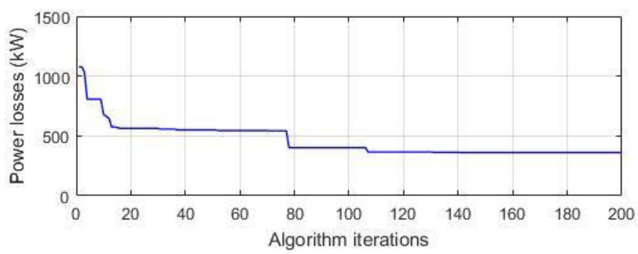

FIGURE 13. Power losses versus GA iterations for case 3.

by [5], [8], and [14] (15,17,26) are shown in Figs 11 and 12. Figure 13 illustrates losses change during DCGA run.

Figure 11 shows the improvement in power quality after reconfiguration and the increase in minimum voltage at bus 12 from 0.9693 p.u. to 0.9716 p.u. Also, Fig. 12 indicates that the proposed framework and other approaches, which could find the optimal configuration, improve the voltage profile compared to the models in [5], [8], and [14]. Moreover, Fig. 13 confirms that the optimal solution suggested by the proposed model is obtained by GA after 35 iterations.

D. CASE 4: 28-BUS DISTRIBUTION NETWORK

This real electrical grid is part of the electrical power distribution system in the city of Koprivnica, Croatia. It consists of 28 buses, one transformer substation of 110/35 kV, two transformer substations of 35/10 kV, 22 loads, and 27 distribution lines. A graph representation of the Koprivnica distribution

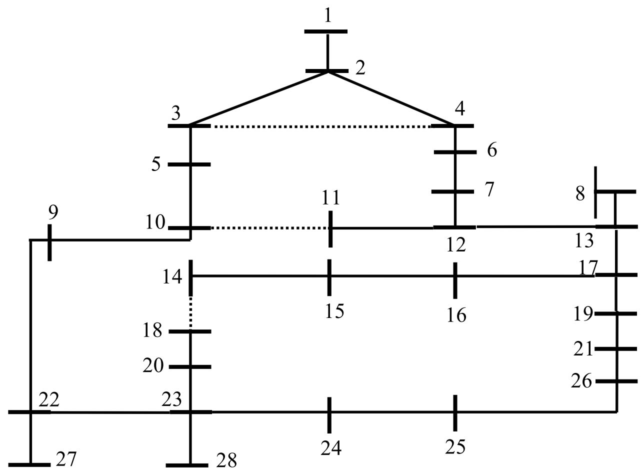

FIGURE 14. Distribution system of Koprivnica [92].

TABLE 4. Numerical results for case 4.

Model	Open Switches	Power Losses (kW) Before Reconfiguration	Power Losses (kW) After Reconfiguration	Time (s)
[92]	11,20,21,28	46	40	–
DCGA	11,20,21,28	46	40	2.87
Proposed	11,20,21,28	46	40	1.11

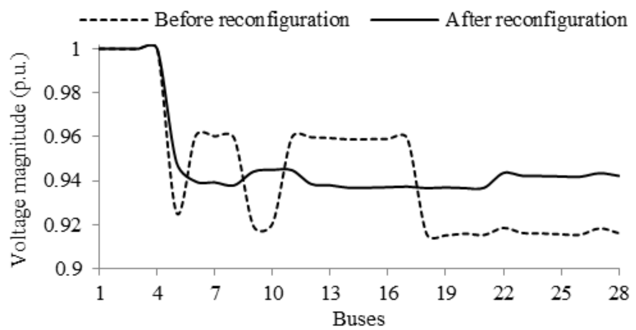

FIGURE 15. The voltage profile before and after reconfiguration of the 28-bus test system.

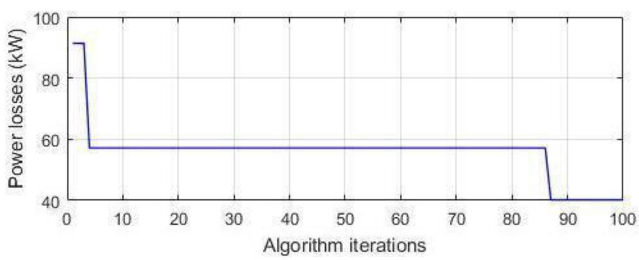

FIGURE 16. Power losses versus GA iterations for case 4.

system is shown in Fig. 14 and its data are available in [92]. Lines and transformers that connect nodes are represented as edges in the graph. Full lines represent distribution branches that are switched on, while dotted lines represent distribution

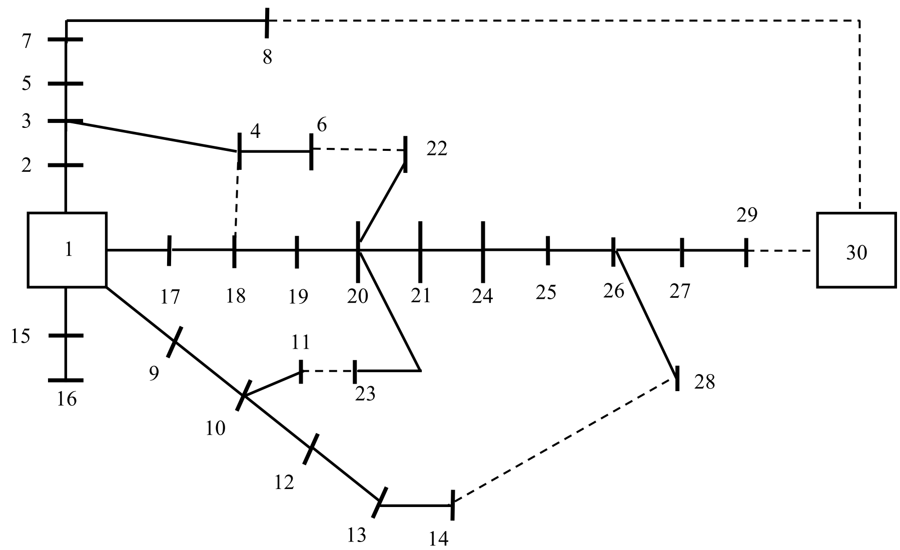

FIGURE 17. The 30-bus test system.

TABLE 5. Numerical results for case 5.

Model	Open Switches	Power Losses (kW)		Time (s)
		Before Reconfiguration	After Reconfiguration	
[93]	3,7, 25,32,33,34	1240	368	–
DCGA	3,7,10,25,32,33	1240	367.3	9.37
Proposed	3,7,10,25,32,33	1240	367.3	2.02

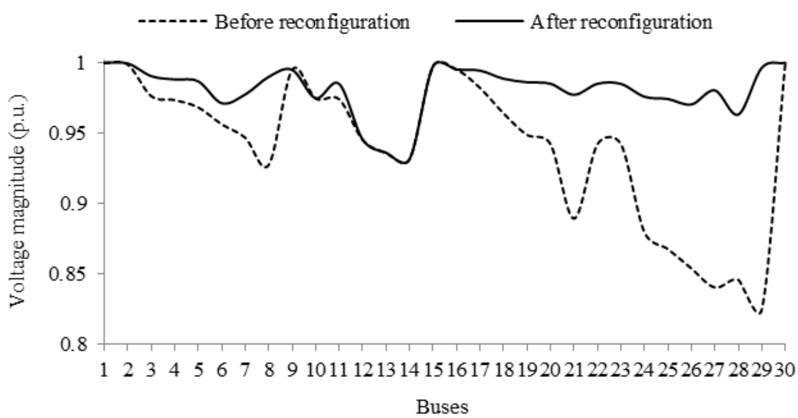

FIGURE 18. The voltage profile before and after reconfiguration of the 30-bus test system by the proposed model.

branches that are switched off. The maximum current of all branches is 500 A. The results are shown in Table 4 and Figs 15 and 16.

Table 4 shows that the proposed model can reach the optimal switching proposal as the method presented in [92] but with less computing time than GA, in which the same solutions were found by DCGA after 88 iterations (according to Fig. 16). Also, the shape of the voltage curve gets more flat after reconfiguration (please see Fig. 15). This happens by filling the valleys and shaving the peaks of voltage profile of buses 5 to 17 and increasing the voltage level of buses 18 to 28. The worst voltage belongs to bus 19 (0.9151 p.u.) that its value is increased by 0.022 (p.u.).

E. CASE 5: 30-BUS DISTRIBUTION NETWORK

The diagram of this test system with six tie lines and 28 normal branches is shown in Fig. 17 and its data are listed in [93].

TABLE 6. Numerical results for case 6.

Model	Open Switches	Power Losses (kW) Before Reconfiguration	After Reconfiguration	Time (s)	Model	Open Switches	Power Losses (kW) Before Reconfiguration	After Reconfiguration	Time (s)
[7]	11,28,31,33,34	205.81	148.86	–	ACO [53]	7,9,14,32,37	202.68	139.55	6.44
[43]	6,9,14,32,37	202.67	142.83	–	[87]	7,9,14,32,37	202.68	139.55	6
[25]	7,10,14,36,37	202.71	142.68	7.2	[67]	7,9,14,32,37	202.68	139.55	5.7
[19]	7,9,14,31,37	194.53	142	0.1	[30]	7,9,14,32,37	202.68	139.55	5.28
[9]	7,9,14,32,37	202.71	141.6	19.1	[49]	7,9,14,32,37	202.68	139.55	3.7
[6]	7,10,14,32,37	205.81	141.54	0.14	HSA [53]	7,10,14,36,37	202.68	139.55	3.27
[46]	7,9,14,32,37	205.81	140.81	0.87	[84]	7,9,14,32,37	202.68	139.55	0.3
[63]	9,28,33,34,36	205.81	140.6	–	[15]	7,9,14,32,37	202.67	139.55	1.99
[83]	7,10,14,32,37	202.71	140.26	–	[44]	7,9,14,32,37	202.67	139.55	1.66
[78]	7,9,14,32,37	203.33	139.98	55.04	[80]	7,9,14,32,37	202.68	139.55	1.5
[62]	7,9,14,32,37	211.22	139.83	–	[21]	7,9,14,32,37	202.68	139.55	0.41
[85]	7,9,14,32,37	203	139.8	6.852	[22]	7,9,14,32,37	202.68	139.55	0.11
[54]	7,9,14,32,37	203	139.8	48	[32]	7,9,14,32,37	202.68	139.5	35.5
[10]	7,9,14,32,37	203.2	139.7	3	DCGA	7,9,14,32,37	202.7	139.5	16.7
[31]	7,9,14,32,37	202.7	139.6	46	[56]	7,9,14,32,37	202.71	139.5	8.1
[8]	7,9,14,32,37	202.67	139.55	–	[57]	7,9,14,32,37	202.68	139.5	8
[45]	7,9,14,32,37	202.68	139.55	–	[64]	7,9,14,32,37	202.68	139.5	6.3
[29]	7,9,14,32,37	202.68	139.55	647.03	[77]	7,9,14,32,37	202.6	139.5	5.7
[50]	7,9,14,32,37	202.67	139.55	19	[33]	7,9,14,32,37	202.68	139.5	3.2
[26]	7,9,14,32,37	202.68	139.55	10.83	[34]	7,9,14,32,37	–	139.5	2.9
[79]	7,9,14,32,37	202.67	139.55	8	Proposed	7,9,14,32,37	202.68	139.5	2. 28
GA [53]	7,10,14,36,37	202.68	139.55	8	QCP [28]	7,9,14,32,37	202.68	139.5	1.43
[88]	7,9,14,32,37	202.68	139.55		[47]	7,9,14,32,37	202.7	139.5	0.5
[61]	7,9,14,32,37	202.7	139.55	7.41	QP [28]	7,9,14,32,37	202.7	139.5	0.21
[66]	7,10,14,36,37	202.68	139.55	7.2	[81]	7,9,14,32,37	202.67	139.5	0.16

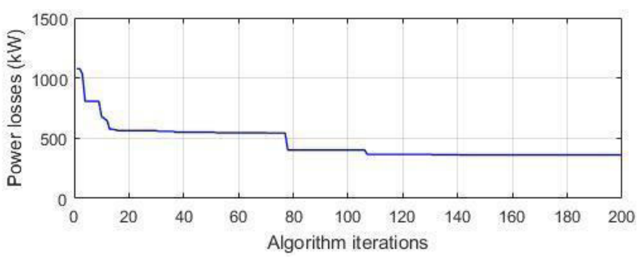

FIGURE 19. Power losses versus GA iterations for case 5.

The nominal values are 1 MVA and 18.6 kV. The results of the proposed technique are shown in Table 5 and Fig. 18. Figure 19 indicates that GA obtains the optimal solution after 141 iterations. The worst voltage magnitudes before and after reconfiguration appear at buses 29 and 14, respectively.

Figure 18 demonstrates an improvement in voltage profile after reconfiguration. According to Table 5, it can be seen that the proposed reconfiguration model reach less losses than the model presented in [93]. Also, the convergence speed of the proposed model is higher than DCGA.

F. CASE 6: 33-BUS DISTRIBUTION NETWORK

The system shown in Fig. 20, includes two feeder substations with three 12.66 kV laterals, five tie switches, and 32 normal branches. The data of this test system are available in [7]. The MVA and kV base are 1 and 12.66, respectively. The voltage of the substation bus (node 0) is assumed 1 per unit. The maximum current flow of each branch is 500 A. The proposed formulation was applied to this test system and the results are listed in Table 6. The voltage profiles of the system before and after reconfiguration are illustrated in Fig. 21. Figure 22 shows the voltage profiles of the optimal configuration (optimal switching arrangement) found by the MICP model and other proposed formulations of Table 6. Also, the convergence process of GA is represented in Fig. 23.

According to Table 6, the proposed reconfiguration strategy could find the accurate solution faster than other methods except of [28], [47], and [81]. It can be seen that performance of model presented by [28] significantly degrades with size of distribution network compared to the proposed model (please refer to Table 12). Also, there is no guarantee for finding optimal solution in large systems by heuristic [47] and metaheuristic [81] methods (please see Case 14).

Figures 21 and 22 show that the optimal configuration presented by the proposed model and other approaches (7,9,14,32,37), as well as switching scenarios proposed by [25], [53], [66] (7,10,14,36,37) and [6], [83] (7,10,14,32,37) improve the voltage profile much better than configurations found by [7], [19], [43], [63]. Due to Fig. 23, it can be said that DCGA converges to the optimal solution after 169 iterations.

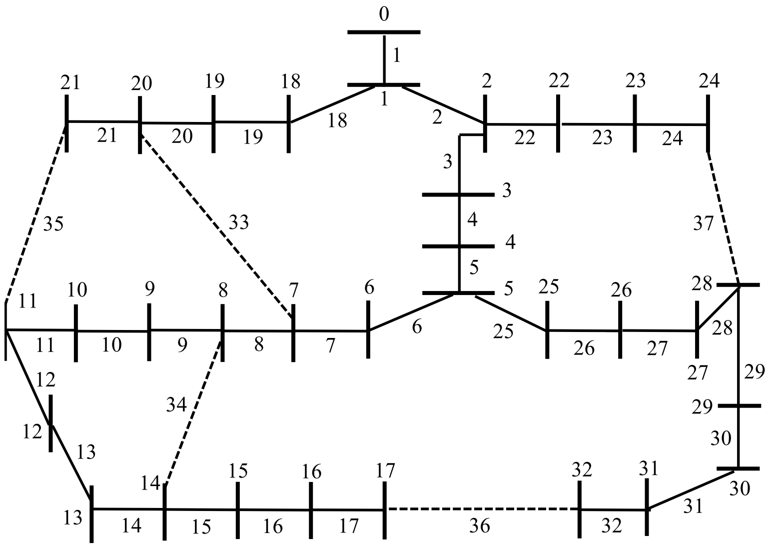

FIGURE 20. The 33-bus test system.

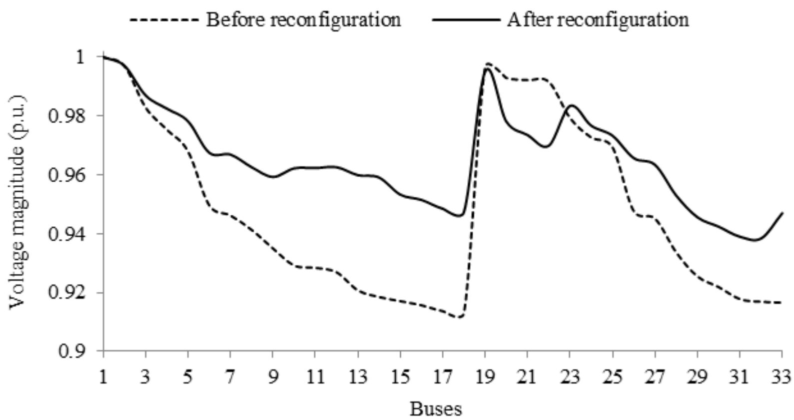

FIGURE 21. Voltage profile before and after reconfiguration of the 33-bus test system by the proposed model.

Accordingly, it can be said that the proposed MICP model can find the optimal switching operation accurately in an acceptable run time.

G. CASE 7: 49-BUS DISTRIBUTION NETWORK

Figure 24 shows the single diagram of the real distribution network of Baghdad city in Iraq. The test system is an 11 kV network with 49 buses, five looping branches (tie lines), 48 sectionalizing switches, and six laterals. The system data and power demand information are available in [94]. Maximum current of each branch is 500 A. The results are listed in Table 7 and shown in Figs 25, 26, and 27.

Due to Table 7, the proposed model could find better open switches and less power losses than [94] in shorter processing time than GA. Also, voltage profiles shown in Fig. 26 demonstrate better voltage profile after reconfiguration of distribution network by the proposed model compared to model of [94]. Therefore, it can be mentioned that the mathematical formulation presented in current research is much better than the model proposed by [94]. According to Fig. 27, GA verifies accuracy of solutions presented by proposed model after 853 iterations.

H. CASE 8: 59-BUS DISTRIBUTION NETWORK

Figure 28 shows a 33 kV real distribution network. This system is a region of the distribution network of the city of Ahvaz in the south of Iran. The 59-bus system includes 58 normal branches (sectionalizing switches) and five tie lines. Line and load data for this real distribution network have been given in [95]. Also, maximum current of each branch is 500 A. Table 8 and Fig 29 show the simulation results after applying the proposed model to this case study system. Convergence process of DCGA is exhibited in Fig. 30.

Comparing the results of [95] with the switching operation and power losses proposed by the MICP model confirms the more accuracy of solution obtained by the proposed

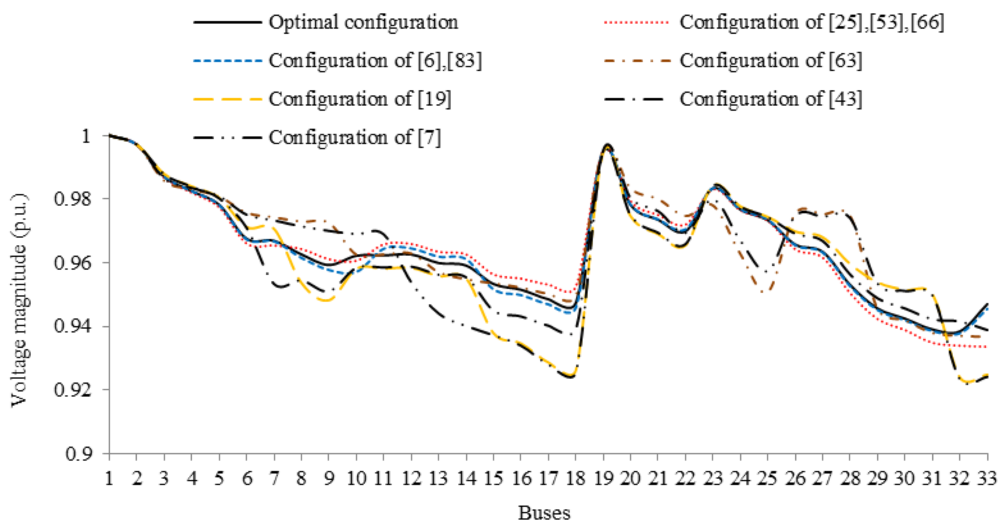

FIGURE 22. The voltage profile of the optimal configuration compared to other configurations of the 33-bus test system.

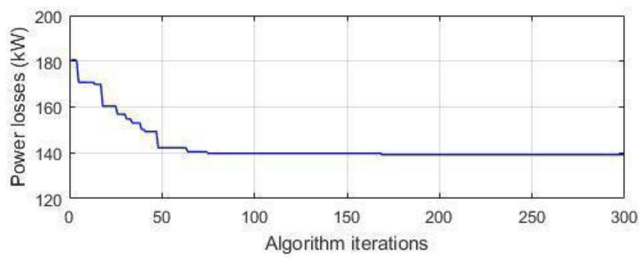

FIGURE 23. Power losses versus GA iterations for case 6.

TABLE 7. Numerical results for case 7.

Model	Open Switches	Power Losses (kW)		Time (s)
		Before Reconfiguration	After Reconfiguration	
[94]	15,34,38,45,52	10.59	8.98	–
DCGA	34,39,45,49,51	10.5	8	21. 7
Proposed	34,39,45,49,51	10.5	8	2.02

model. Also, Table 8 shows too higher convergence speed (very shorter run time) of the proposed reconfiguration technique than that of [95] and DCGA (GA approaches the accurate solution after 1250 iterations due to Fig. 30). Also, Fig. 29 shows voltage improvement of the system after reconfiguration, because of increase in voltage level of buses 8 to 59. The minimum voltage, in which was 0.9767 p.u. at buses 56 to 58, is increased to 0.9847 p.u. at bus 59.

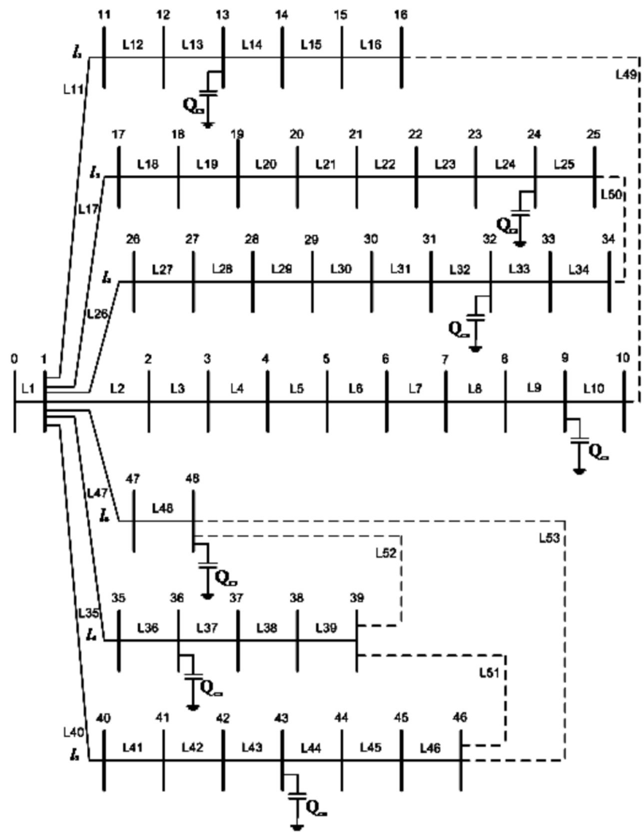

FIGURE 24. Baghdad distribution system [94].

I. CASE 9: 69-BUS DISTRIBUTION NETWORK

This 12.66 kV radial distribution system has 69 nodes (buses), 68 normal switches, and five tie lines, as shown in Fig. 31. Data of this system has been presented in [96]. The base power and rated voltage are 100 MVA and 12.66 kV. The proposed mathematical model was applied to under study network and the results were provided in Table 9 and Figs 32 and 33. In order to show accuracy of the solutions proposed by MICP model, the power losses reduction during optimization by GA is represented in Fig 34. It should be noted that the network losses before reconfiguration were 225 kW.

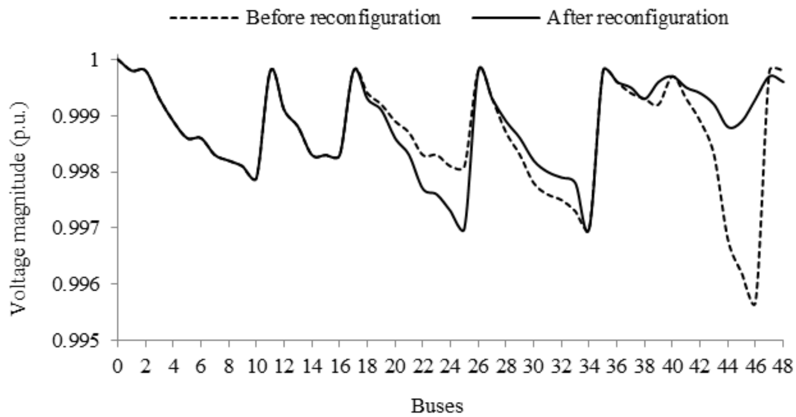

FIGURE 25. The voltage profile before and after reconfiguration of the 49-bus test system by the proposed model.

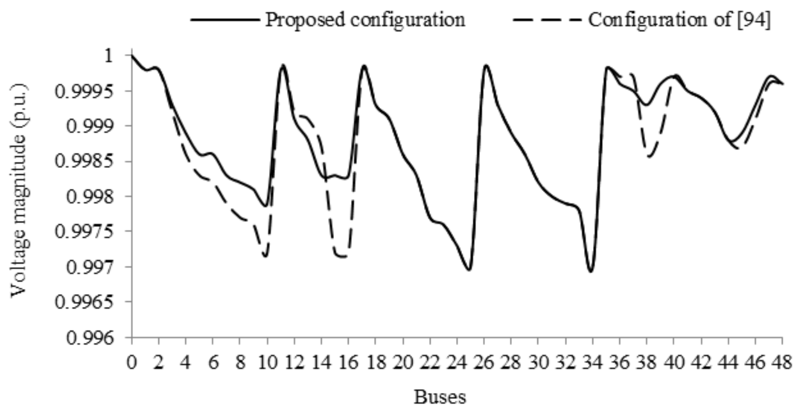

FIGURE 26. The voltage profile after reconfiguration of the 49-bus test system by the proposed model compared to the model of [94].

TABLE 8. Numerical results for case 8.

Model	Open Switches	Power Losses (kW)		Time (s)
		Before Reconfiguration	After Reconfiguration	
[95]	25,31,39,40,62	178.66	131.71	20
DCGA	25,31,40,41,62	178.66	131.69	48.88
Proposed	25,31,40,41,62	178.66	131.69	2.8

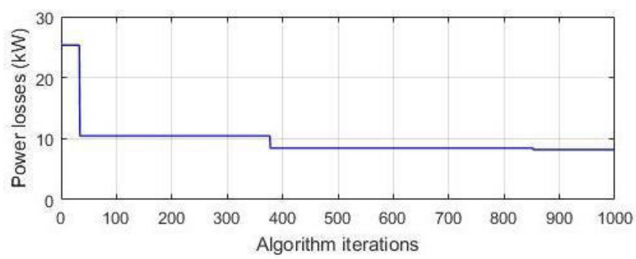

FIGURE 27. Power losses versus GA iterations for case 7.

For a better comparison, only voltage profiles of configurations (switching scenarios) which lead to the minimum power losses (99.62 kW) are drawn in Fig. 33. The voltage profiles of other configurations are inferior to these three curves.

Among different models presented in Table 9, the proposed approach is better, because first it converges to the optimal solution faster than others and second it improves the voltage profile more efficiently than all approaches except for models mentioned in [16], [17], [36] [100], and [102]. However, the difference between the voltage curve of the proposed model and the best one is very small. In simple terms, only the voltage of bus 58 is increased by 0.042 p.u. using models of [16], [17], [36] [100], and [102] compared to the proposed technique, but the proposed model solves the DSR problem more quickly than the fastest method among

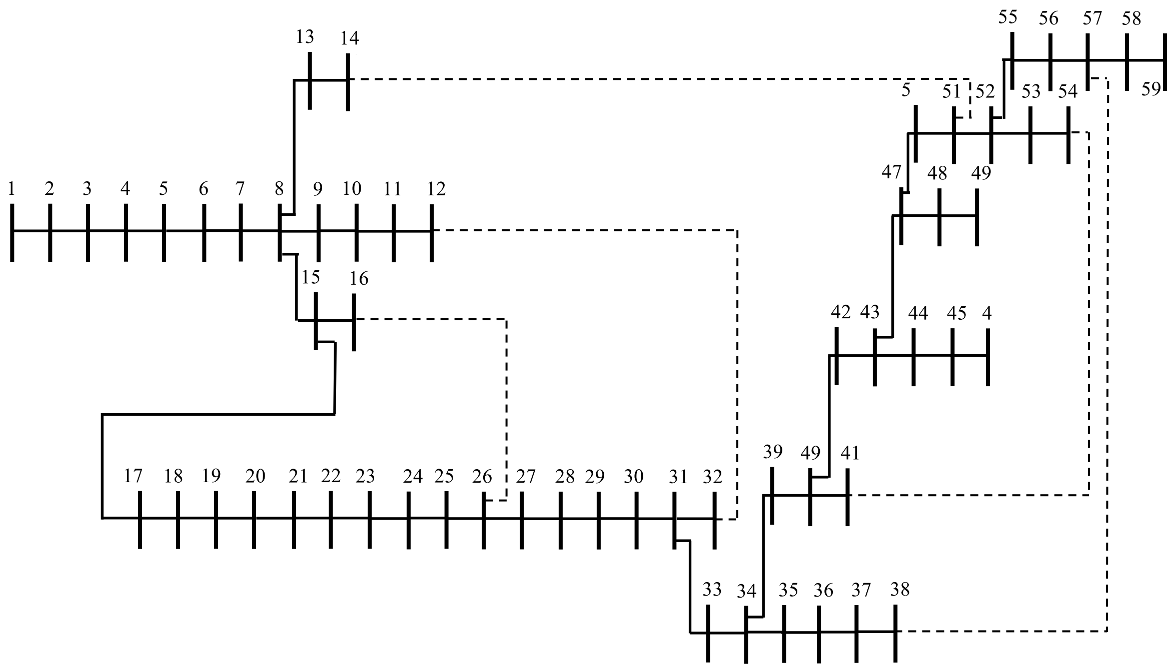

FIGURE 28. The 59-bus distribution system [95].

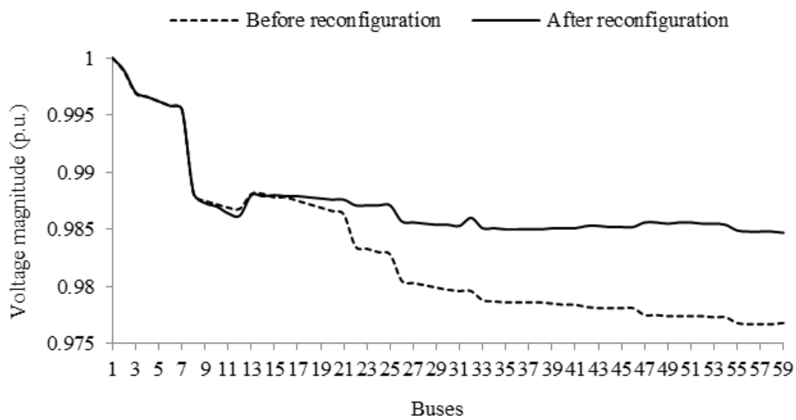

FIGURE 29. The voltage profile before and after reconfiguration of the 59-bus test system.

these approaches, i.e. [36], that could solve the problem in 12.5 seconds.

J. CASE 10: 70-BUS DISTRIBUTION NETWORK

The tested system is an 11 kV radial distribution network with two substations, four feeders, 70 buses, and 76 branches (including tie lines) as shown in Fig. 35. Data for this system are available in [104]. The nominal power of the network is 100 kVA. Table 10 shows proposed configurations, power loss amounts, and computing times. The active power losses of initial network (before reconfiguration) are 227.5 kW.

Also, Figs 36 and 37 show voltage profiles before and after network reconfiguration for different switching scenarios. Figure 38 illustrates power loss changes in terms of genetic algorithm iterations. According to Fig. 36, even

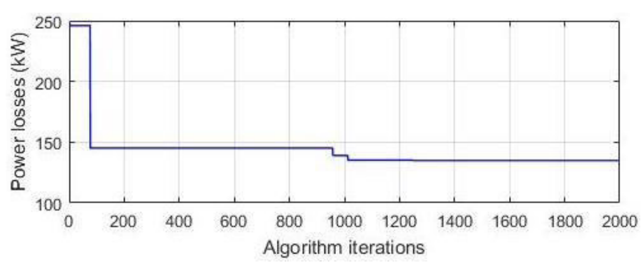

FIGURE 30. Power losses versus GA iterations for case 8.

though the voltages of 21 buses (buses 2 to 12, 16 to 23, and 68 and 69) have been decreased after reconfiguration, voltages of 44 buses (buses 24 to 67) were increased. It means

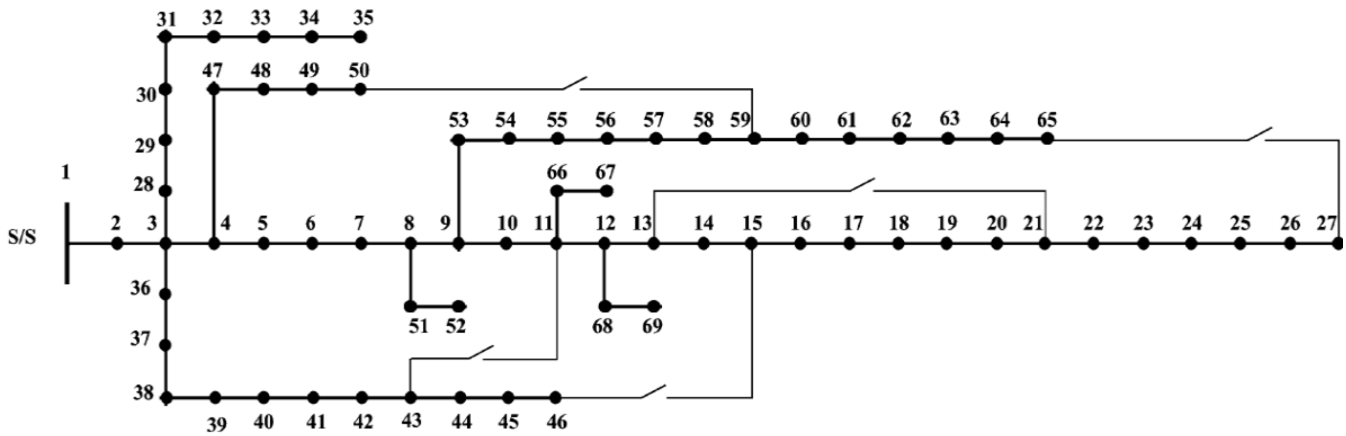

FIGURE 31. The 69-bus test system [96].

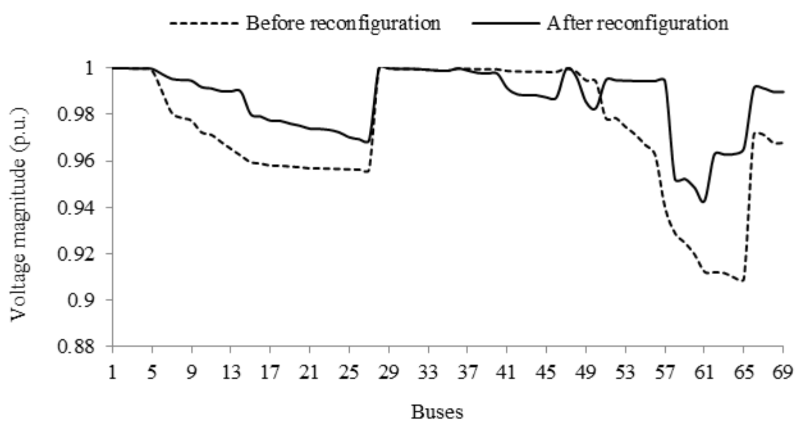

FIGURE 32. The voltage profile before and after reconfiguration of the 69-bus test system by the proposed model.

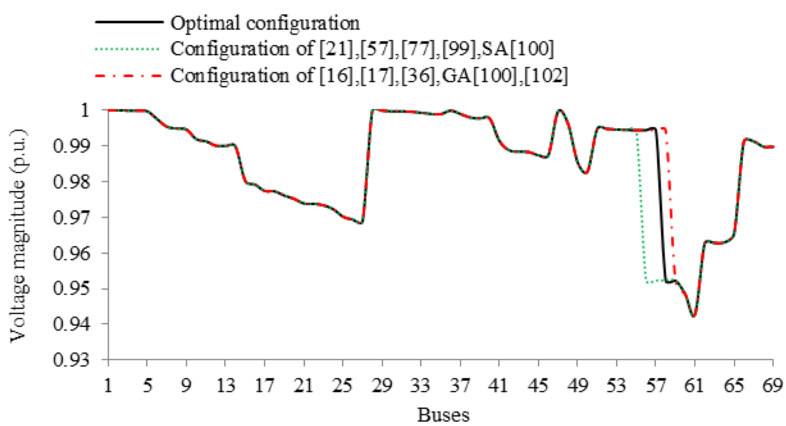

FIGURE 33. The voltage profile of the optimal configuration compared to other configurations of the 69-bus test system.

that almost 70% of voltage profile of network buses has been improved after reconfiguration. Also, Fig. 37 shows that the worst voltage profile is related to reconfiguration strategies presented in [67] and [104] to [107]. Although switching operations of GAMT [66] and [108] improve voltage profile a little bit at 17 buses (buses 30 to 42, 45 to 49, and 61 to 64), they degrade significantly the voltage profile at 18 buses (buses 2 to 15, 43, 44, 50, 68, and 69) compared to the optimal configuration proposed by the MICP, DCGA, BGA [66], and [84].

TABLE 9. Numerical results after reconfiguration for case 9.

Model	Open Switches	Power Losses (kW)	Time (s)	Model	Open Switches	Power Losses (kW)	Time (s)
[97]	14,23,51,60,72	136.87	37	[95]	14,57,61,69,70	99.62	–
FGA [96]	12,20,58,64,69	113.8	50	GA [100]	14,58,61,69,70	99.62	1181
BGA [96]	12,20,58,64,69	113.8	25	SA [101]	14,57,61,69,70	99.62	250
Heuristic [30]	11,14,21,56,62	106.67	–	SA [100]	14,55,61,69,70	99.62	165
GA [25]	14,53,61,69,70	103.29	–	[57]	14,55,61,69,70	99.62	150
RGA [25]	13,17,55,61 69	100.28	–	DCGA	14,57,61,69,70	99.62	37.96
[83]	12,57,61,69,70	99.82	–	[102]	14,58,61,69,70	99.62	20.69
[45]	13,55,61,69,70	99.72	–	Efficient SA [101]	14,57,61,69,70	99.62	20.57
NCUP [30]	13,58,61,69,70	99.72	–	[68]	14,57,61,69,70	99.62	20.2
[16]	14,58,61,69,70	99.62	–	[36]	14,58,61,69,70	99.62	12.5
[98]	14,56,61,69,70	99.62	–	[77]	14,55,61,69,70	99.62	8
[21]	14,55,61,69,70	99.62	–	[103]	14,57,61,69,70	99.62	7
[17]	14,58,61,69,70	99.62	–	Proposed	14,57,61,69,70	99.62	6.17
[99]	14,55,61,69,70	99.62	–	–	–	–	–

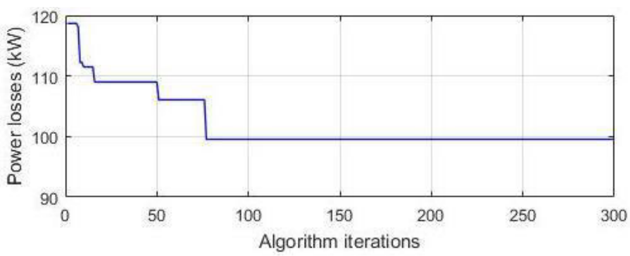

FIGURE 34. Power losses versus GA iterations for case 9.

The performance of models proposed by [31] and [32] is very similar to the MICP model from the voltage improvement point of view, because they could improve half of voltage profile of network buses and degrade half other. Therefore, the proposed switching operation (optimal configuration) can improve the voltage profile much better than models of [67] and [104] to [107] and even better than approaches presented by GAMT [66] and [108].

Only switching scenario of [31] and [32] can compete with the proposed model, but the model presented in this study is better than [31] and [32] because of less power losses. Thus, the proposed model is more effective than other formulations presented in Table 10 because not only it finds the lowest power losses as much as minimum losses found by DCGA, BGA [66], and [84], but it reaches the optimal solution much faster than them. Also, the optimal configuration found by MICP same as DCGA, BGA [66], and [84] enhances the power quality as much as configuration presented in [31] and [32] and more efficiently than other proposed configurations.

K. CASE 11: DISTRIBUTION NETWORK OF TAIWAN POWER COMPANY (TPC)

As shown in Fig. 39, this accrual 11.4 kV network consists of two substations, 11 feeders, 83 normal switches, and 13 tie

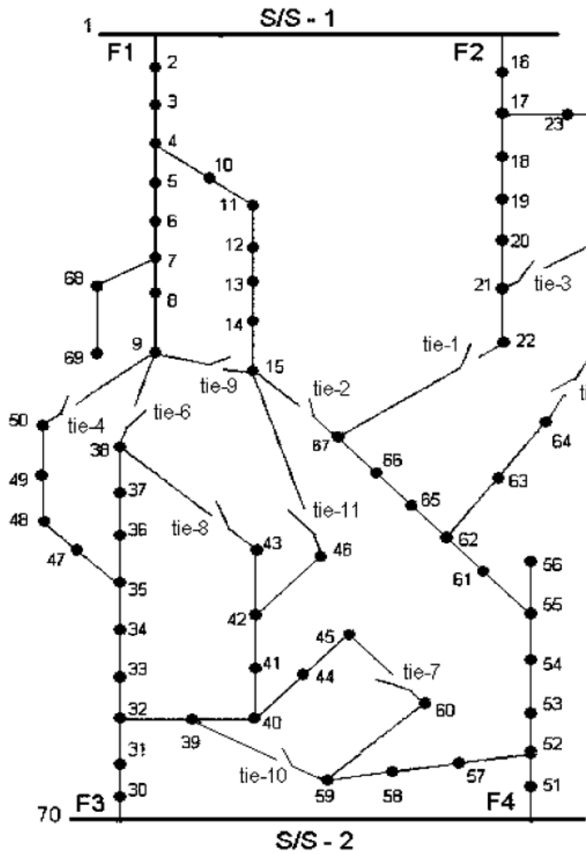

FIGURE 35. The 70-bus test system [104].

lines, in which its data have been presented in [18]. The current-carrying capacity of each line (I_{ij}^{max}) is 410 A. The power base value for this system is 10 kVA. The active power loss of initial network is 532 kW. Table 11 and Figs 40 and 41 show the simulation results of the proposed model compared to other reconfiguration techniques for this real test system.

TABLE 10. Numerical results after reconfiguration for case 10.

Model	Open Switches	Power Losses (kW)	Time (s)	Model	Open Switches	Power Losses (kW)	Time (s)
[105]	14,28,39,46,51,67,70,71,73,76,79	205.32	8	[32]	14,30,45,51,66,70,75–79	201.44	485
[106], [107]	14,28,39,46,51,67,70,71,73,76,79	205.32	5.4	[31]	14,30,45,51,66,70,75–79	201.44	5.7
[104]	14,28,39,46,51,67,70,71,73,76,79	205.32	3	BGA [66]	13,30,45,51,66,70,75–79	201.4	1900
Heuristic [67]	13,28,45,51,67,70,73,75,76,78,79	203.67	7633.3	[84]	13,30,45,51,66,70,75–79	201.4	91.13
SOReco [67]	13,28,45,51,67,70,73,75,76,78,79	203.67	4.64	DCGA	13,30,45,51,66,70,75–79	201.4	69.27
GAMT [66]	14,30,38,46,51,66, 70,71,76,77,79	203.17	160	Proposed	13,30,45,51,66,70,75–79	201.4	4.9
[108]	30,46,51,66,70,71,75–79	202.18	–	–	–	–	–

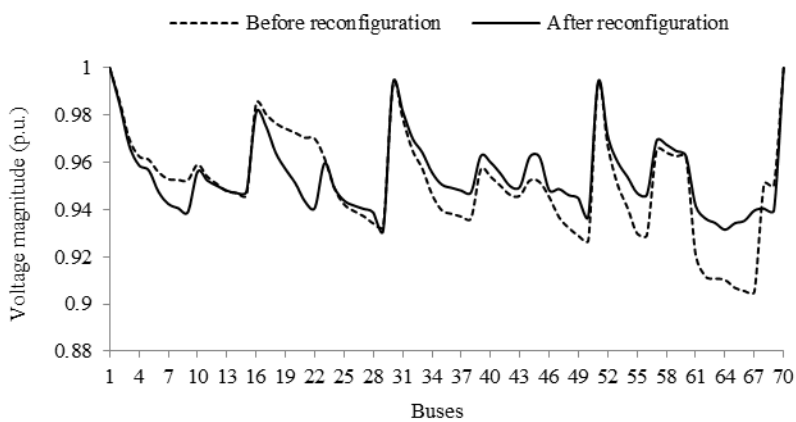

FIGURE 36. The voltage profile before and after reconfiguration of the 70-bus test system by the proposed model.

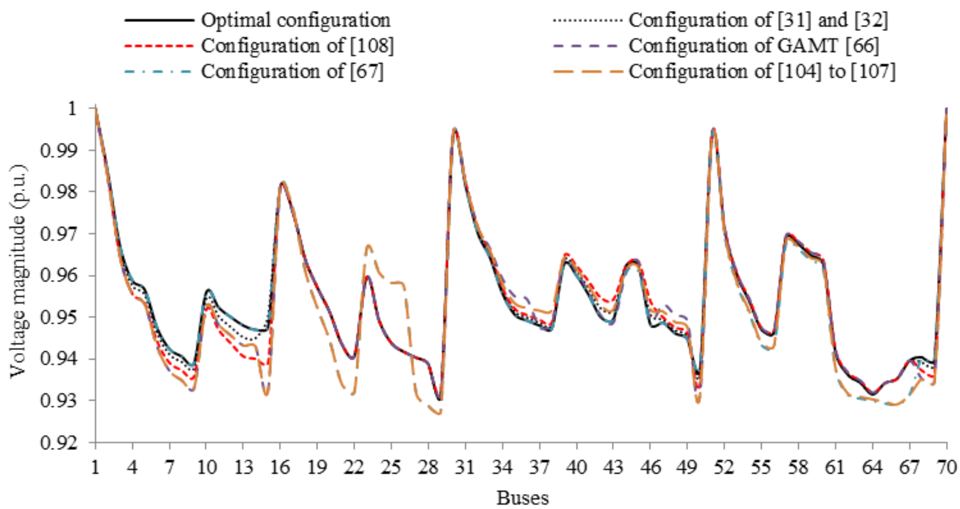

FIGURE 37. The voltage profile of the optimal configuration compared to other configurations of the 70-bus test system.

Furthermore, convergence process of GA is shown in Fig. 42. It i seen that the GA finds the optimal configuration after 4663 iterations. It should be mentioned that bus 0 represents buses connected to the substation 1 (S/S1) and bus 84 indicates buses are connected to the substation 2 (S/S2).

Table 11 confirms that the proposed model can find the optimal configuration and the minimum active power losses faster than other methods. Also, Fig. 40 illustrates that the profile of bus voltages is improved significantly after reconfiguration.

Moreover, Fig. 41 shows that the optimal configuration introduced by the proposed methodology and other models with the same switching scenario (7,13,34,39,42,55,62,72, 83,86,89,90,92) enhances the voltage profile and therefore

TABLE 11. Numerical results after reconfiguration for case 11.

Model	Open Switches	Power Losses (kW)	Time (s)	Model	Open Switches	Power Losses (kW)	Time (s)
[88]	7,14,34,39,42,55,62,72,83,86,88,90,92	482.14	13	[29]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	–
GA [24]	7,33,55,61,72,83,86,88,89,90,92,93,95	471.51	–	[65]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	450
[6]	7,13,34,39,41,55,62,72,83,86,89,90,92	471.1	–	MINLP [27]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	245.4
[44]	7,13,34,39,41,55,62,72,83,86,89,90,92	471.1	–	MILP [27]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	207.7
ACO [24]	7,13,34,39,41,55,62,72,83,86,89,90,92	471.1	–	DCGA	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	109
[91]	7,13,34,39,41,55,62,72,83,86,89,90,92	471.1	318	[84]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	95.88
ACO [52]	7,13,34,39,41,55,62,72,83,86,89,90,92	471.1	303.7	GA [53]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	37.98
[82]	7,13,34,39,41,55,62,72,83,86,89,90,92	471.1	241.5	ACO [53]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	19.74
[80]	7,13,34,39,41,55,62,72,83,86,89,90,92	471.1	113.2	HBMO [53]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	17.1
[18]	7,13,34,39,41,55,62,72,83,86,89,90,92	471.1	36.15	HSA [53]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	9.87
[15]	7,13,34,39,42,62,72,83,84,86,89,90,92	470.5	170	[48]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	7.75
SA [46]	7,13,34,39,42,62,72,83,84,86,89,90,92	470.5	22.06	[67]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	7
GA [46]	7,13,34,39,42,63,72,83,84,86,89,90,92	470.1	69	[30]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	5.28
[49]	7,13,34,39,42,63,72,83,84,86,89,90,92	470.1	7.8	Proposed	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	4.95
[21]	7,13,34,39,42,55,62,72,83,86,89,90,92	469.88	–	–	–	–	–

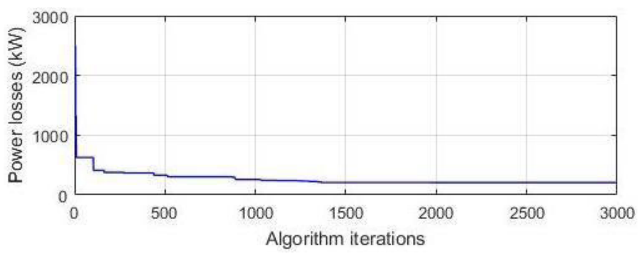

FIGURE 38. Power losses versus GA iterations for case 10.

network power quality better than configurations proposed by other formulations of Table 11. These facts show higher efficiency of the proposed model compared to other methods for reconfiguration of the TPC system.

L. CASE 12: 119-BUS DISTRIBUTION NETWORK

This test system, as shown in Fig. 43, is an 11 kV distribution network with three feeders, 118 lines, and 15 tie switches. The parameters and related data of the system can be found in [56]. The base MVA and kV are 1 and 11, respectively. Table 12 shows the relevant results. Also, profiles of bus voltages were depicted in Figs 44 and 45. It should be noted that the active power loss of the network before reconfiguration has been 1298 kW. Figure 46 shows that DCGA converges to the same optimal solution found by proposed model after 2077 iterations.

Although most methods listed in Table 12, including the proposed approach could find the minimum power losses (869.7 kW) as well as the optimal switching scenario (24,27,35,40,43,52,59,72,75,96,98,110,123,130,131), the proposed MICP technique reaches the optimal solution faster than the others except for [32]. However, formulation of the proposed model is easier than MILP presented in [32]. Unlike model of [32], MICP can be directly applied to DSR problem without any approximation and linearization of non-linear terms of losses and power flow equations. Choosing improper values for uncertain parameters of MILP such as number of piecewise functions, lines slopes and each line interval on horizontal axis decreases the model accuracy considerably. As shown in Figs 44 and 45, the configurations of [57], GA [25], and RGA [25] may improve the voltage profile as effective as the optimal configuration proposed by MICP model compared to the base case, however, their proposed switching scenarios causes a large amount of active losses in the network. Therefore, it can be said that the proposed reconfiguration strategy solves the DSR problem more efficiently than other proposed methods.

M. CASE 13: 136-BUS DISTRIBUTION NETWORK

As shown in Fig. 47, this real network is part of the Tres Lagoas distribution system in Brazil and its data are available in [112]. It has 156 branches and 21 tie switches with nominal voltage and nominal power of 13.8 kV and 100 kVA, respectively. Also, the initial power losses and the maximum current of each branch are 320.37 kW and 200 A, respectively. The proposed model was applied to this real test system and the results were presented in Table 13. Figure 48 illustrates the better power quality because of nodal voltage improvement after reconfiguration.

Because of the large number of voltage curves due to many different switching strategies listed in Table 13, the voltage profiles of optimal switching operation (7,35,51, 90,96,106,118,126,135,137,138,141,142,144–148, 150,151, 155) was compared to only configurations of [31] and [33] as well as [71] and [86] (those found the closer power losses to the minimum amount (280.19 kW)). From Table 13, it can be seen that the proposed model can find the optimal solution much faster than formulations which could approach the same minimum power losses. According to Fig. 49, even

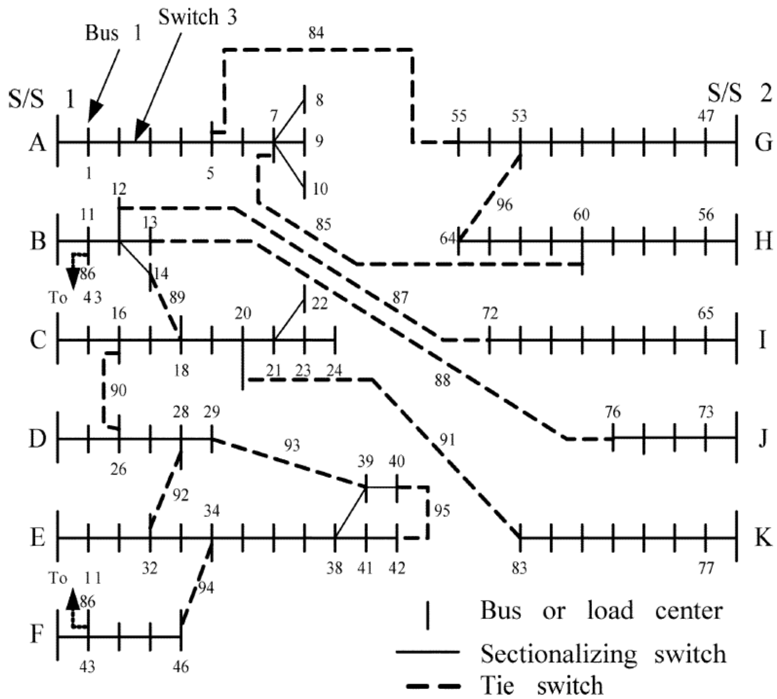

FIGURE 39. Distribution system of TPC [18].

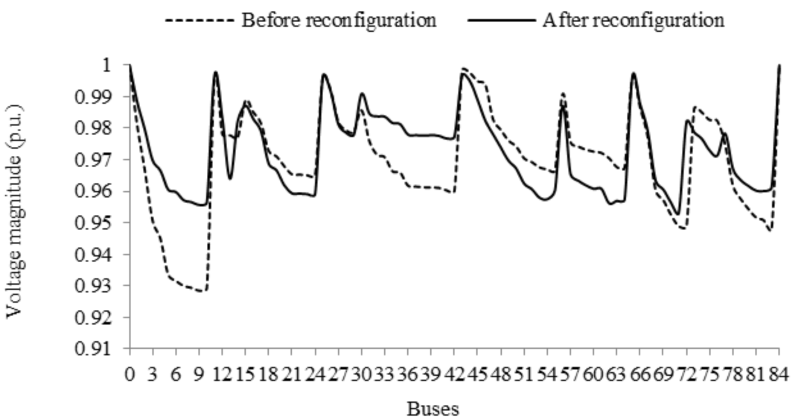

FIGURE 40. The voltage profile before and after reconfiguration of the TPC system by the proposed model.

though other switching operations (configurations) could improve the voltage profile nearly like the proposed model, they are not as accurate and fast as the MICP formulation. Figure 50 proves accuracy of the solution obtained by the proposed model. Therefore, the proposed framework is more efficient for reconfiguration of real large-scale distribution networks compare to other methods listed in the table.

N. CASE 14: 203-BUS DISTRIBUTION NETWORK

In order to illustrate the effectiveness of the proposed methodology in larger systems, the proposed approach was applied to 203-bus distribution network and results were listed in Table 14. Also, the losses changes versus GA iterations were drawn in Fig. 51. The initial configuration of this real 13.8 kV distribution network is shown in Fig. 52. The system data can be found in [113]. The base power and maximum current of branches are 1 MVA and 2000 A, respectively. Figure 53 shows that voltage levels are decreased at buses 3 to 57 (55 buses) and then they are increased at the rest buses compared to initial case. It means that more than 80% of voltage profile is improved after reconfiguration. Also, Fig. 54 indicates that performance of the proposed model is better than DCGA and the formulation presented in [113] from the voltage improvement point of view. The MICP model could optimize the network losses more accurately

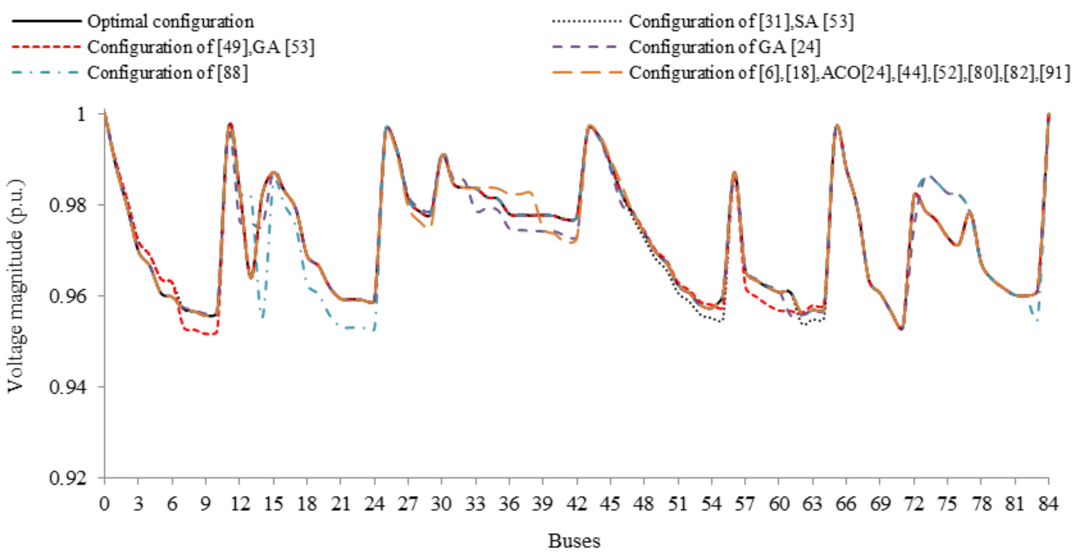

FIGURE 41. The voltage profile of the optimal configuration compared to other configurations of the TPC system.

TABLE 12. Numerical results after reconfiguration for case 12.

Model	Open Switches	Power Losses (kW)	Time (s)	Model	Open Switches	Power Losses (kW)	Time (s)
[109]	5,27,34,43,47,54,61,71,74,83,96,99, 110,125,131	980.54	–	[84]	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	869.7	430.74
GA [25]	24,35,40,43,49,51,62,73,74,77,83, 110,120,126,131	885.56	24.45	DCGA	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	869.7	390.7
TS [57]	23,27,33,40,43,49,52,62,72,74,77, 83,110,126,131	884.163	–	[36]	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	869.7	42.13
RGA [25]	23,27,33,40,43,49,52,62,73,74,77, 83,110,126,131	883.13	17.53	[56]	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	869.7	9.38
[110]	24,27,35,40,43,52,59,72,75,96,99, 110,123,130,131	870.33	704.1	HSA [25]	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	869.7	8.61
[21]	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	869.7	–	[111]	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	869.7	7.64
QCP [28]	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	869.7	1009	Proposed	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	869.7	4.95
[31]	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	869.7	39.4	MILP [32]	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	869.7	2.8
MTS [57]	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	869.7	18000	–	–	–	–

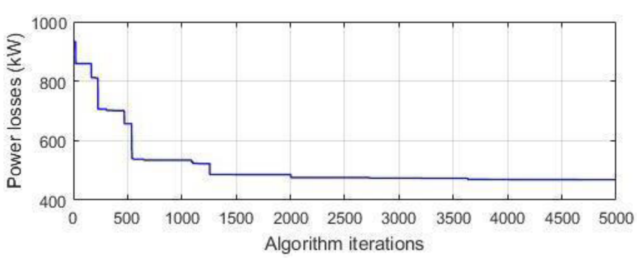

FIGURE 42. Power losses versus GA iterations for case 11.

than [113] and GA. The results show that heuristic and meta-heuristic algorithms cannot guarantee optimality of solutions in large size distribution networks because of algorithm capture in local minima. Accordingly, the results analysis proves high accuracy of the proposed method for reconfiguration of real large distribution networks compared to model of [113] and GA method.

V. ADVANTAGES OF PROPOSED METHODOLOGY COMPARED TO OTHER METHODS

In this section, the main features of the model are compared with some other important formulations to more clarify the advantages of the proposed method.

Coding MINLP formulation of [4] by B&B algorithm is relatively hard, while the implementation of MICP model is easy in AMPL.

The DC load flow based formulations presented in [5] cannot solve the DSR problem precisely because of ignorance

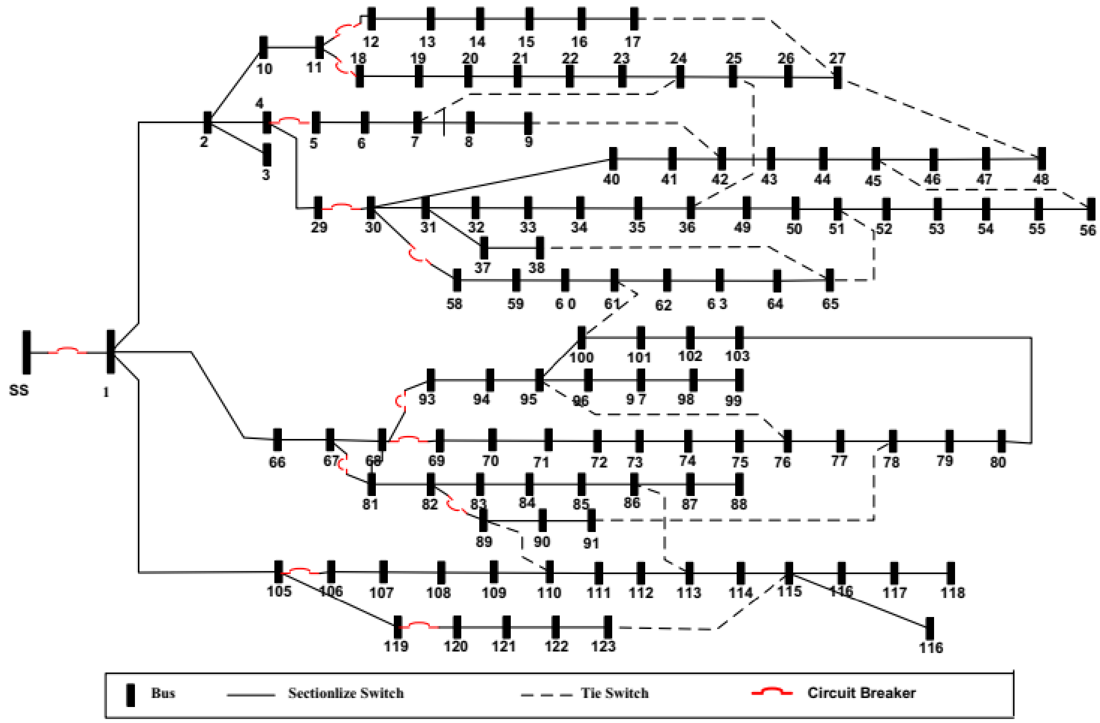

FIGURE 43. The 119-bus test system.

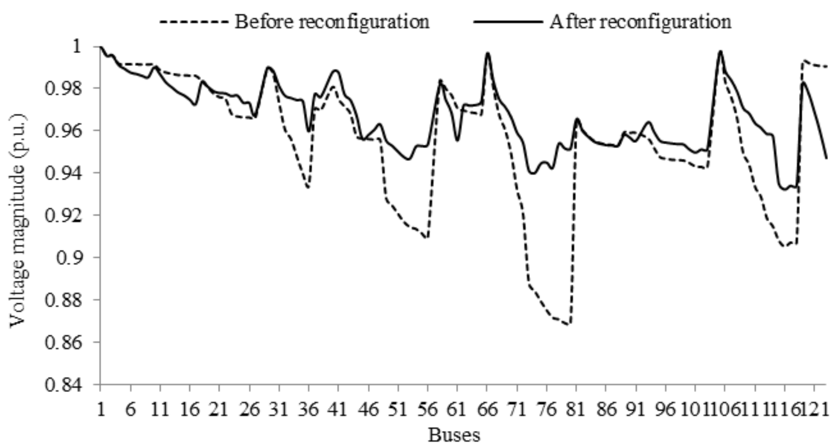

FIGURE 44. The voltage profile before and after reconfiguration of the 119-bus test system by the proposed model.

of reactive power component, while the MICP solves the problem using AC load flow model.

Metaheuristic algorithms used in [17] (SA), [18] (MIHDE), [25] (HSA), and [36] (GA) cannot guarantee optimality of solutions in large-scale distribution networks, while the proposed method is able to solve the DSR problem accurately for large-sized systems.

Estimation of power losses in [6], [8], and [19] has effectively reduced accuracy of the proposed formulations in comparison with the MICP model.

Time-consuming point to point searching process of the models proposed in [7] and [12] prevent their applications to medium and large-scale distribution networks, while the MICP model can be applied to distribution systems with any size.

Unlike the MICP model, the formulation presented in [9] is not efficient because of appearance of many non-feasible (non-radial) solutions during optimization.

Simplification of load flow equations in [10] and piecewise linear approximations of power losses in [29], as well

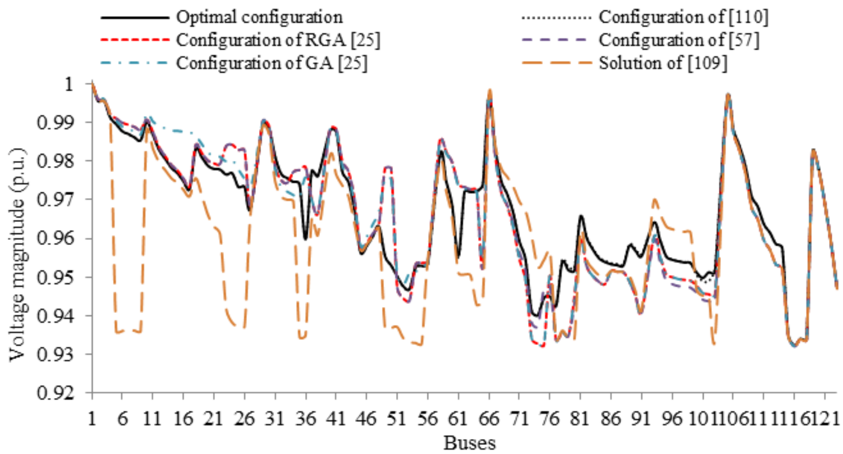

FIGURE 45. The voltage profile of the optimal configuration compared to other configurations of the 119-bus test system.

TABLE 13. Numerical results after reconfiguration for case 13.

Model	Open Switches	Power Losses (kW)	Time (s)	Model	Open Switches	Power Losses (kW)	Time (s)
[45]	7,9,38,51,55,90,92,95,104,106,120,126, 128,135,138,141,144–146,148,150	286	–	[71]	7,51,53,84,90,96,106,118,126,128,137–139,141,144,145,147,148,150,151,156	280.22	3600
[112]	51,106,136–139,141–152,154–156	285.5	24.45	[26]	7,35,51,90,96,106,118,126,135,137,138, 141,142,144–148,150,151,155	280.19	4473
[30]	7,38,51,55,90,97,106,118,126,137,138, 141,144–148,150–152,155	282.77	–	[27]	7,35,51,90,96,106,118,126,135,137,138, 141,142,144–148,150,151,155	280.19	1800
[73]	51,53,90,96,106,118,136–139,141, 144–148, 150,151,154–156	281.7	17.53	[32]	7,35,51,90,96,106,118,126,135,137,138, 141,142,144–148,150,151,155	280.19	1785
[49]	7,38,51,54,84,90,96,106,119,126,135,137, 138,141,144,145,147,148,150,151,155	281.02	704.1	[84]	7,35,51,90,96,106,118,126,135,137,138, 141,142,144–148,150,151,155	280.19	894.2
[72]	7,38,51,53,90,96,106,118,126,128,137, 138,141,144–148,150,151,156	280.4	–	DCGA	7,35,51,90,96,106,118,126,135,137,138, 141,142,144–148,150,151,155	280.19	300.4
[33]	7,38,51,54,84,90,96,106,118,126,128,135, 137,138,141,144,145,147,148,150,151	280.38	1009	[34]	7,35,51,90,96,106,118,126,135,137,138, 141,142,144–148,150,151,155	280.19	24.8
[31]	7,38,51,54,84,90,96,106,118,126,128,135, 137,138,141,144,145,147,148,150,151	280.38	39.4	Proposed	7,35,51,90,96,106,118,126,135,137,138, 141,142,144–148,150,151,155	280.19	9.5
[86]	7,51,53,84,90,96,106,118,126,128,137–139,141,144,145,147,148,150,151,156	280.22	5120	–	–	–	–

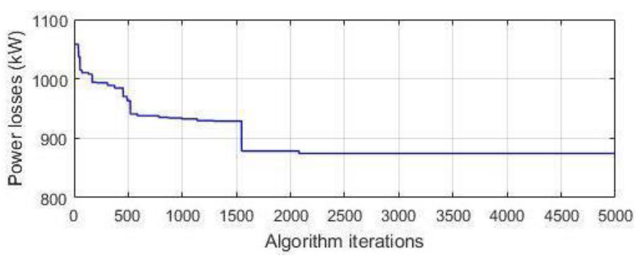

FIGURE 46. Power losses versus GA iterations for case 12.

as linearization of quadratic terms of objective functions in [32] and [33] have relatively decreased processing time of DSR problem. However, efficiency and accuracy of formulations presented in [10], [29], [32], and [33] can be reduced in real applications compared to the exact (without any simplification, linearization, and approximation) MICP model. Moreover, additional mathematical efforts needs for linearization and approximations of non-linear terms in [29], [32], and [33] in contrast to MICP model.

Representing the DSR problem in terms of mutual and linear circuit currents same as [13] is difficult for medium and large size distribution systems. However, this kind of representation is not required in the proposed formulation.

Although maximum two load flows were needed to solve the DSR problem in the formulation presented by [14], implementation of model of [14] has restricted to small-sized

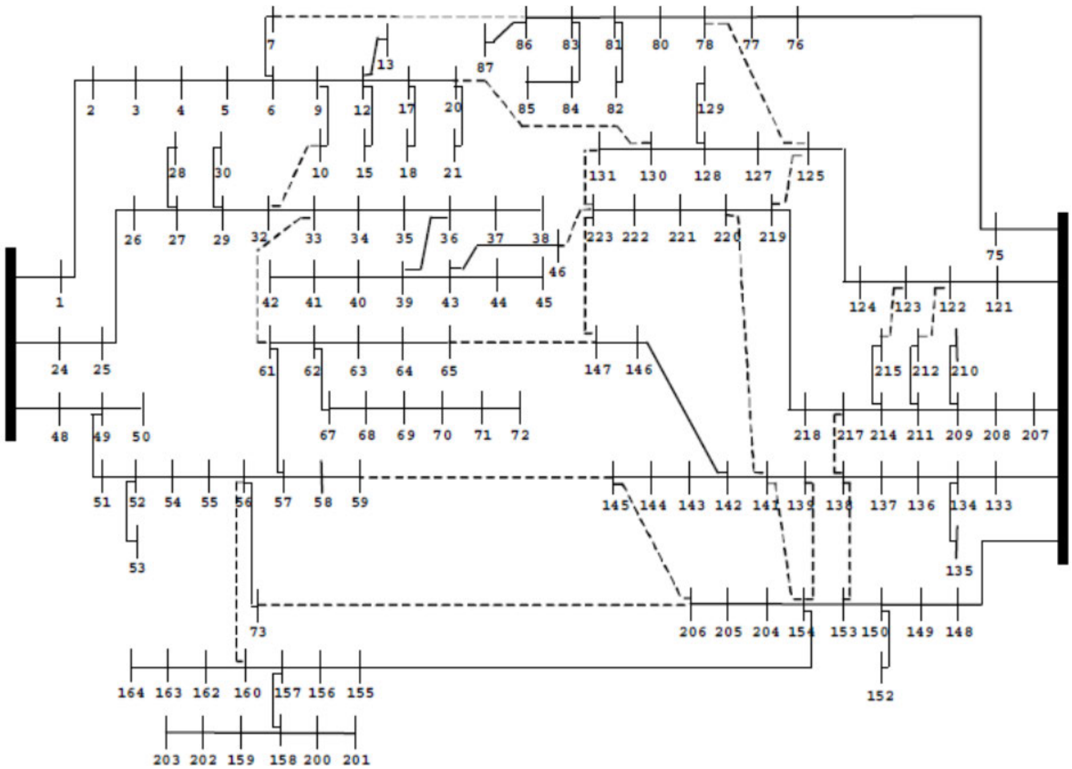

FIGURE 47. The 136-bus distribution system [112].

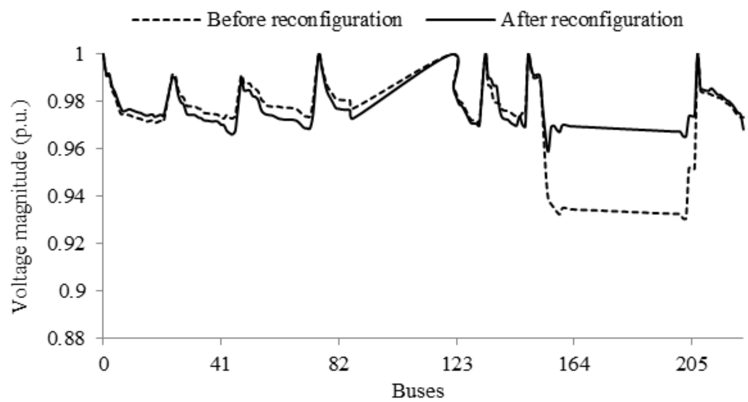

FIGURE 48. Voltage profile before and after reconfiguration of the 136-bus test system by the proposed model.

TABLE 14. Numerical results for case 14.

Model	Open Switches	Power Losses (kW)		Time (s)
		Before Reconfiguration	After Reconfiguration	
[113]	29,66,74,83,111,118,125,131,135,136,140, 177,199,202,208	548.9	537.1	49.98
DCGA	12,29,66,74,83,111,118,125,131,135,136,140, 199,202,208	548.9	536.9	677.98
Proposed	12,26,43,82,118,131,133,140,168,202,203, 208,212,213,214	548.9	511.19	948.64

distribution systems. Nonetheless, the MICP model can be applied to every distribution network without any load flow calculations.

The DAOP based model proposed in [15] cannot guarantee the optimal solutions for large distribution systems because of its heuristic nature, while the model presented

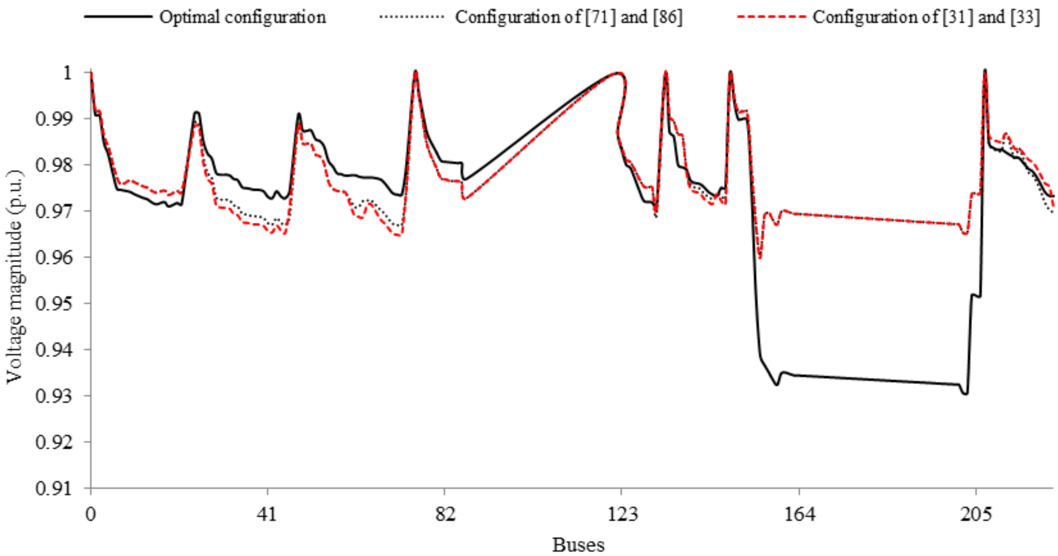

FIGURE 49. Voltage profile after reconfiguration compared to other proposed models for the 136-bus test system.

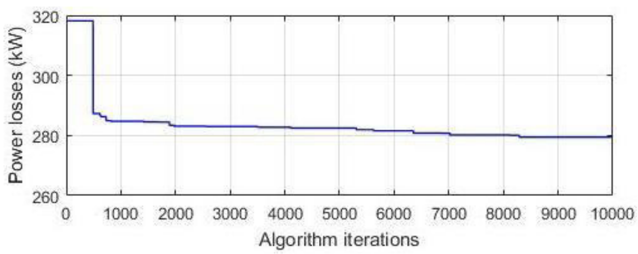

FIGURE 50. Power losses versus GA iterations for case 13.

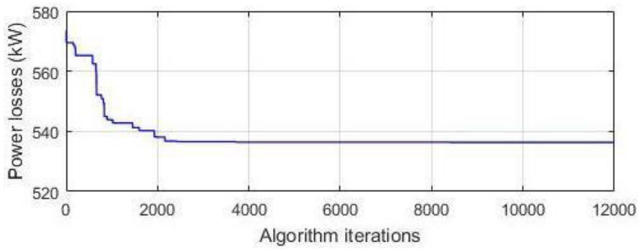

FIGURE 51. Power losses versus GA iterations for case 14.

TABLE 15. Reconfiguration results of proposed model for each day based on actual variable load amounts of RECT system.

Case Studies	Open Switches	Energy Losses (kWh)
Case 1	5	13.98
Case 2	3,9	22.66
Case 3	17,19,26	7911.6
Case 4	11,20,21,28	664.09
Case 5	3,7,10,25,32,33	6186.6
Case 6	7,9,14,32,37	2351.74
Case 7	34,39,45,49,51	123.46
Case 8	25,31,40,41,62	2241.47
Case 9	14,57,61,69,70	1678.01
Case 10	13,30,45,51,66,70,75–79	3385.52
Case 11	7,13,34,39,42,55,62,72,83,86,89, 90,92	7945.99
Case 12	24,27,35,40,43,52,59,72,75,96,98, 110,123,130,131	14655.41
Case 13	7,35,51,90,96,106,118,126,135,137, 138,141,142,144–148,150,151,155	4748.9
Case 14	12,26,43,82,118,131,133,160,168, 202,203,208,212,213,214	9420.08

in current study has found accurate solutions in all test systems.

Although formulations presented in [20], [21], and [30] based on sensitivity analysis causes decrease in processing time of DSR problem, presenting active losses sensitivity in terms of the branch impedances makes implementation of models proposed by [20], [21], and [30] harder than MICP method.

The decomposition method of [22] has been applied to a small size distribution system because of its hard implementation compared to MICP.

The formulation of [31] cannot be applied to non-planar networks and computational time of models presented in [26] and [27] are much more than the proposed method.

Allocating imagery circles with different geometrical radius to network loops in [16] is not an exact way for DSR modeling.

Although the performance of the model presented in [34] is better than the models of [27] and [32], its computation time and simplicity are more and less than models proposed in [27] and [32], respectively.

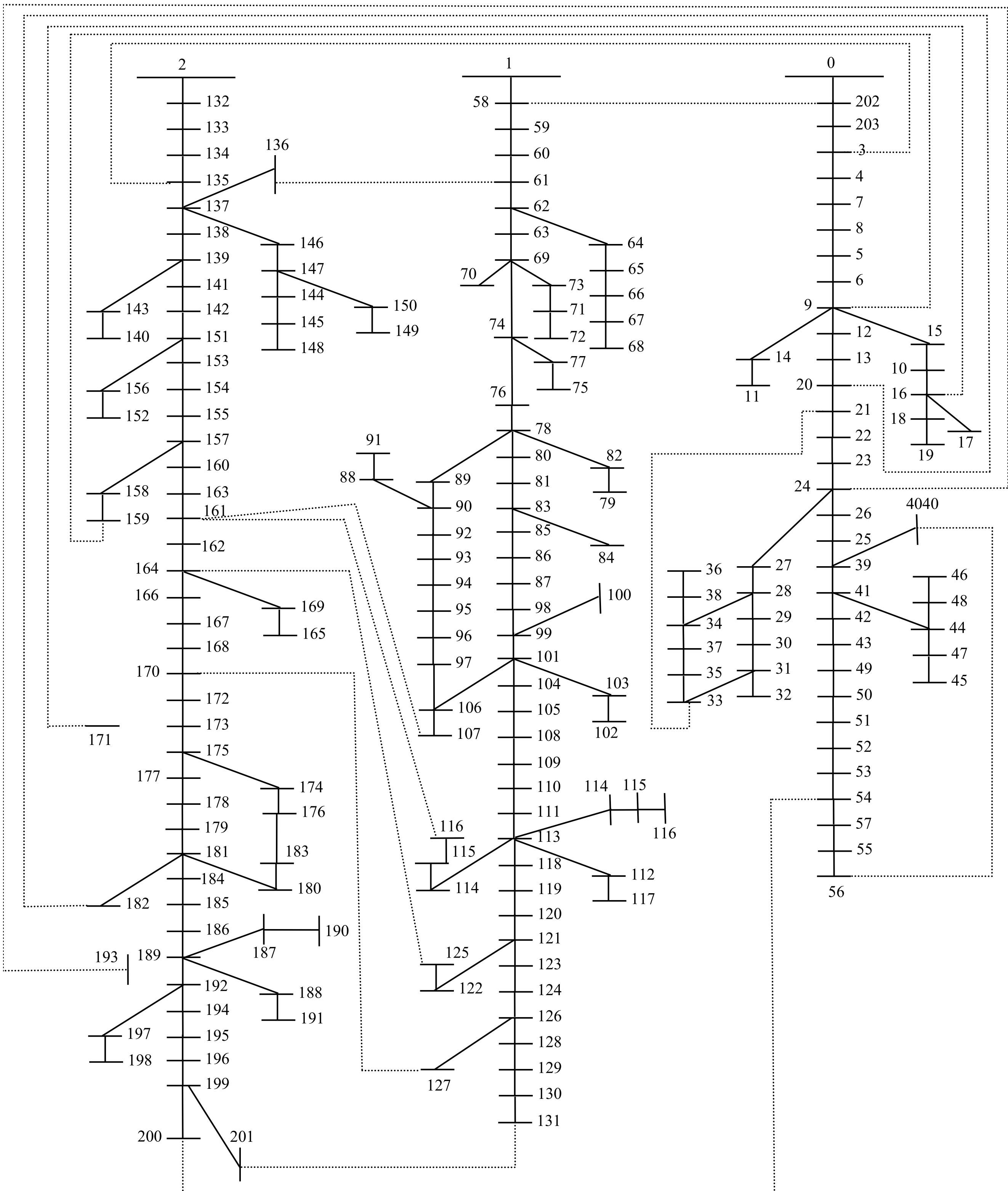

FIGURE 52. The 203-bus distribution system.

Unlike MICP model, efficiency of mathematical formulation described in [28] has been reduced with increase in size of network.

High complexity of two-stage reconfiguration algorithm used in [35] decreases possibility of model implementation in real applications, while the

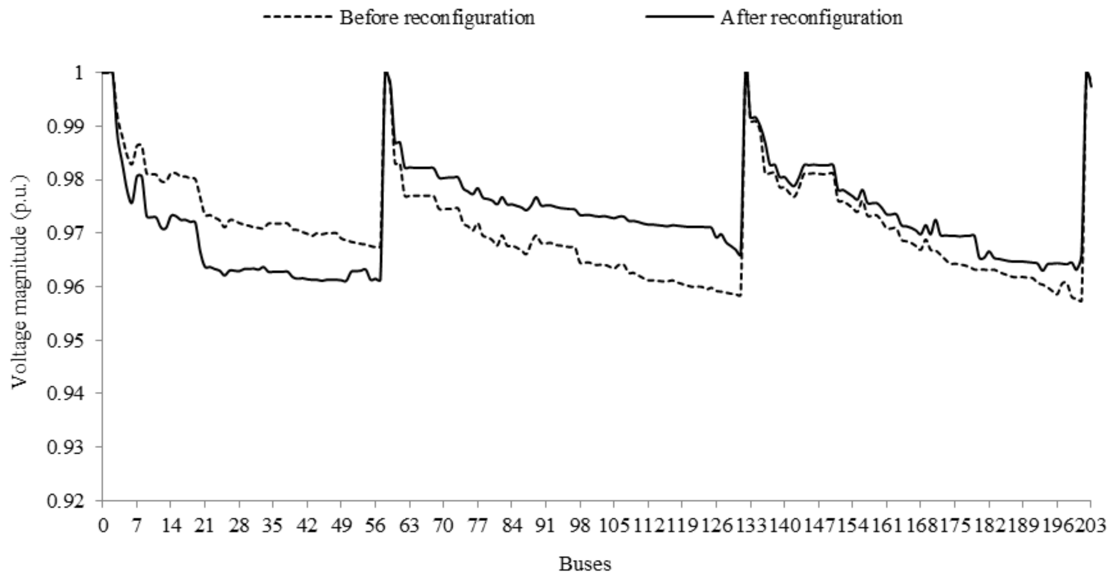

FIGURE 53. Voltage profile before and after reconfiguration of the 203-bus test system by the proposed model.

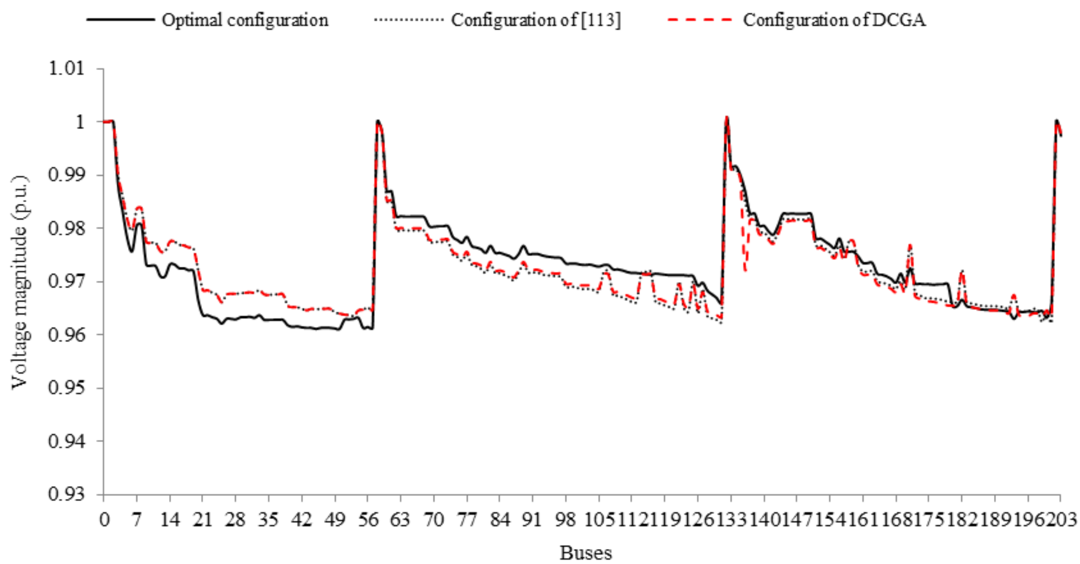

FIGURE 54. The voltage profile after reconfiguration of the 203-bus test system by the proposed model compared to the model of [113] and DCGA.

MICP model can be easily applied to practical DSR problems.

VI. CONCLUSION

This paper presents an efficient convex mixed-integer conic programming (MICP) model for reconfiguration of radial distribution systems using AMPL. The model was applied to different types of distribution networks and results were compared to solutions obtained by decimal codification genetic algorithm (DCGA) and other existing reconfiguration methods.

Main properties of the proposed formulation are short computing time, high precision (without any approximation and linearization), and simple implementation. Another important feature of MICP model is that it can be solved by every commercial solver.

Simulation results reveal that the proposed model not only reduces power losses effectively, but also improves the voltage profile of the system. Computing time of the proposed approach is less than other reconfiguration techniques which could find the accurate optimal solutions, except for models of [28], [47], and [81] in small size 33-bus test system and model of [32] in medium size TPC network. However, convergence speed of MICP model is much higher than method of [32] in all other case studies. Also processing time of model presented by [28] is much higher than proposed model in

TABLE 16. Selected configurations in each hour based on actual variable load amounts of RECT system for case 1.

H	Open Switches	H	Open Switches	H	Open Switches	H	Open Switches
1	5	7	5	13	5	19	5
2	5	8	5	14	5	20	5
3	5	9	5	15	5	21	5
4	5	10	5	16	5	22	5
5	5	11	5	17	5	23	5
6	5	12	5	18	5	24	5

TABLE 17. Selected configurations in each hour based on actual variable load amounts of RECT system for case 2.

H	Open Switches	H	Open Switches	H	Open Switches	H	Open Switches
1	3,9	7	3,9	13	3,9	19	3,9
2	3,9	8	3,9	14	3,9	20	3,9
3	3,9	9	3,9	15	3,9	21	3,9
4	3,9	10	3,9	16	3,9	22	3,9
5	3,9	11	3,9	17	3,9	23	3,9
6	3,9	12	3,9	18	3,9	24	3,9

TABLE 18. selected configurations in each hour based on actual variable load amounts of RECT system for case 3.

H	Open Switches	H	Open Switches	H	Open Switches	H	Open Switches
1	17,19,26	7	17,19,26	13	17,19,26	19	17,19,26
2	17,19,26	8	17,19,26	14	17,19,26	20	17,19,26
3	17,19,26	9	17,19,26	15	17,19,26	21	17,19,26
4	17,19,26	10	17,19,26	16	17,19,26	22	17,19,26
5	17,19,26	11	17,19,26	17	17,19,26	23	17,19,26
6	17,19,26	12	17,19,26	18	17,19,26	24	17,19,26

TABLE 19. Selected configurations in each hour based on actual variable load amounts of RECT system for case 4.

H	Open Switches	H	Open Switches	H	Open Switches
1	11,20,21,28	9	11,20,21,28	17	11,20,21,28
2	11,20,21,28	10	11,20,21,28	18	11,20,21,28
3	11,20,21,28	11	11,20,21,28	19	11,20,21,28
4	11,20,21,28	12	11,20,21,28	20	11,20,21,28
5	11,20,21,28	13	11,20,21,28	21	11,20,21,28
6	11,20,21,28	14	11,20,21,28	22	11,20,21,28
7	11,20,21,28	15	11,20,21,28	23	11,20,21,28
8	11,20,21,28	16	11,20,21,28	24	11,20,21,28

119-bus test system. The efficiency of formulations presented in [28] and [32] has been significantly reduced in large distribution networks (119 and 136-bus test systems) compared to the proposed model. Moreover, models of [47] and [81] cannot guarantee optimal solutions in large size distribution networks because of their heuristic and metaheuristic-based formulations.

TABLE 20. Selected configurations in each hour based on actual variable load amounts of RECT system for case 5.

H	Open Switches	H	Open Switches	H	Open Switches
1	3,7,10,25,32,33	9	3,7,10,25,32,33	17	3,7,10,25,32,33
2	3,7,10,25,32,33	10	3,7,10,25,32,33	18	3,7,10,25,32,33
3	3,7,10,25,32,33	11	3,7,10,25,32,33	19	3,7,10,25,32,33
4	3,7,10,25,32,33	12	3,7,10,25,32,33	20	3,7,10,25,32,33
5	3,7,10,25,32,33	13	3,7,10,25,32,33	21	3,7,10,25,32,33
6	3,7,10,25,32,33	14	3,7,10,25,32,33	22	3,7,10,25,32,33
7	3,7,10,25,32,33	15	3,7,10,25,32,33	23	3,7,10,25,32,33
8	3,7,10,25,32,33	16	3,7,10,25,32,33	24	3,7,10,25,32,33

TABLE 21. Selected configurations in each hour based on actual variable load amounts of RECT system for case 6.

H	Open Switches	H	Open Switches	H	Open Switches
1	7,9,14,32,37	9	7,9,14,32,37	17	7,9,14,32,37
2	7,9,14,32,37	10	7,9,14,32,37	18	7,9,14,32,37
3	7,9,14,32,37	11	7,9,14,32,37	19	7,9,14,32,37
4	7,9,14,32,37	12	7,9,14,32,37	20	7,9,14,32,37
5	7,9,14,32,37	13	7,9,14,32,37	21	7,9,14,32,37
6	7,9,14,32,37	14	7,9,14,32,37	22	7,9,14,32,37
7	7,9,14,32,37	15	7,9,14,32,37	23	7,9,14,32,37
8	7,9,14,32,37	16	7,9,14,32,37	24	7,9,14,32,37

TABLE 22. Selected configurations in each hour based on actual variable load amounts of RECT system for case 7.

H	Open Switches	H	Open Switches	H	Open Switches
1	34,39,45,49,51	9	34,39,45,49,51	17	34,39,45,49,51
2	34,39,45,49,51	10	34,39,45,49,51	18	34,39,45,49,51
3	34,39,45,49,51	11	34,39,45,49,51	19	34,39,45,49,51
4	34,39,45,49,51	12	34,39,45,49,51	20	34,39,45,49,51
5	34,39,45,49,51	13	34,39,45,49,51	21	34,39,45,49,51
6	34,39,45,49,51	14	34,39,45,49,51	22	34,39,45,49,51
7	34,39,45,49,51	15	34,39,45,49,51	23	34,39,45,49,51
8	34,39,45,49,51	16	34,39,45,49,51	24	34,39,45,49,51

TABLE 23. Selected configurations in each hour based on actual variable load amounts of RECT system for case 8.

H	Open Switches	H	Open Switches	H	Open Switches
1	25,31,40,41,62	9	25,31,40,41,62	17	25,31,40,41,62
2	25,31,40,41,62	10	25,31,40,41,62	18	25,31,40,41,62
3	25,31,40,41,62	11	25,31,40,41,62	19	25,31,40,41,62
4	25,31,40,41,62	12	25,31,40,41,62	20	25,31,40,41,62
5	25,31,40,41,62	13	25,31,40,41,62	21	25,31,40,41,62
6	25,31,40,41,62	14	25,31,40,41,62	22	25,31,40,41,62
7	25,31,40,41,62	15	25,31,40,41,62	23	25,31,40,41,62
8	25,31,40,41,62	16	25,31,40,41,62	24	25,31,40,41,62

The proposed framework is an efficient and robust model for reconfiguration of every distribution network (planar or non-planar and small- or large-sized distribution systems) including several transfer and substation buses. It can guarantee radiality of distribution network after reconfiguration without any isolated buses and can find highly effective

TABLE 24. Selected configurations in each hour based on actual variable load amounts of RECT system for case 9.

H	Open Switches	H	Open Switches	H	Open Switches
1	14,57,61,69,70	9	14,57,61,69,70	17	14,57,61,69,70
2	14,57,61,69,70	10	14,57,61,69,70	18	14,57,61,69,70
3	14,57,61,69,70	11	14,57,61,69,70	19	14,57,61,69,70
4	14,57,61,69,70	12	14,57,61,69,70	20	14,57,61,69,70
5	14,57,61,69,70	13	14,57,61,69,70	21	14,57,61,69,70
6	14,57,61,69,70	14	14,57,61,69,70	22	14,57,61,69,70
7	14,57,61,69,70	15	14,57,61,69,70	23	14,57,61,69,70
8	14,57,61,69,70	16	14,57,61,69,70	24	14,57,61,69,70

TABLE 25. Selected configurations in each hour based on actual variable load amounts of RECT system for case 10.

H	Open Switches	H	Open Switches
1	13,30,45,51,66,70,75–79	13	13,30,45,51,66,70,75–79
2	13,30,45,51,66,70,75–79	14	13,30,45,51,66,70,75–79
3	13,30,45,51,66,70,75–79	15	13,30,45,51,66,70,75–79
4	13,30,45,51,66,70,75–79	16	13,30,45,51,66,70,75–79
5	13,30,45,51,66,70,75–79	17	13,30,45,51,66,70,75–79
6	13,30,45,51,66,70,75–79	18	13,30,45,51,66,70,75–79
7	13,30,45,51,66,70,75–79	19	13,30,45,51,66,70,75–79
8	13,30,45,51,66,70,75–79	20	13,30,45,51,66,70,75–79
9	13,30,45,51,66,70,75–79	21	13,30,45,51,66,70,75–79
10	13,30,45,51,66,70,75–79	22	13,30,45,51,66,70,75–79
11	13,30,45,51,66,70,75–79	23	13,30,45,51,66,70,75–79
12	13,30,45,51,66,70,75–79	24	13,30,45,51,66,70,75–79

TABLE 26. Selected configurations in each hour based on actual variable load amounts of RECT system for case 11.

H	Open Switches	H	Open Switches
1	7,13,34,39,42,55,62,72, 83,86,89,90,92	13	7,13,34,39,42,55,62,72, 83,86,89,90,92
2	7,13,34,39,42,55,62,72, 83,86,89,90,92	14	7,13,34,39,42,55,62,72, 83,86,89,90,92
3	7,13,34,39,42,55,62,72, 83,86,89,90,92	15	7,13,34,39,42,55,62,72, 83,86,89,90,92
4	7,13,34,39,42,55,62,72, 83,86,89,90,92	16	7,13,34,39,42,55,62,72, 83,86,89,90,92
5	7,13,34,39,42,55,62,72, 83,86,89,90,92	17	7,13,34,39,42,55,62,72, 83,86,89,90,92
6	7,13,34,39,42,55,62,72, 83,86,89,90,92	18	7,13,34,39,42,55,62,72, 83,86,89,90,92
7	7,13,34,39,42,55,62,72, 83,86,89,90,92	19	7,13,34,39,42,55,62,72, 83,86,89,90,92
8	7,13,34,39,42,55,62,72, 83,86,89,90,92	20	7,13,34,39,42,55,62,72, 83,86,89,90,92
9	7,13,34,39,42,55,62,72, 83,86,89,90,92	21	7,13,34,39,42,55,62,72, 83,86,89,90,92
10	7,13,34,39,42,55,62,72, 83,86,89,90,92	22	7,13,34,39,42,55,62,72, 83,86,89,90,92
11	7,13,34,39,42,55,62,72, 83,86,89,90,92	23	7,13,34,39,42,55,62,72, 83,86,89,90,92
12	7,13,34,39,42,55,62,72, 83,86,89,90,92	24	7,13,34,39,42,55,62,72, 83,86,89,90,92

solutions in a short computing time compared to other reconfiguration approaches proposed in the literature. Moreover, the proposed formulation is highly flexible allowing additional constraints or considerations to be easily included in order to increase accuracy and decrease computation time.

TABLE 27. Selected configurations in each hour based on actual variable load amounts of RECT system for case 13.

H	Open Switches	H	Open Switches
1	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155	13	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155
2	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155	14	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155
3	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155	15	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155
4	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155	16	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155
5	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155	17	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155
6	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155	18	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155
7	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155	19	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155
8	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155	20	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155
9	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155	21	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155
10	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155	22	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155
11	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155	23	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155
12	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155	24	7,35,51,90,96,106,118,126, 135,137,138,141,142,144–148,150,151,155

TABLE 28. Selected configurations in each hour based on actual variable load amounts of RECT system for case 12.

H	Open Switches	H	Open Switches
1	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131	13	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131
2	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131	14	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131
3	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131	15	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131
4	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131	16	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131
5	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131	17	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131
6	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131	18	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131
7	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131	19	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131
8	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131	20	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131
9	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131	21	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131
10	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131	22	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131
11	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131	23	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131
12	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131	24	24,27,35,40,43,52,59,72, 75,96,98,110,123,130,131

TABLE 29. Selected configurations in each hour based on actual variable load amounts of RECT system for case 14.

H	Open Switches	H	Open Switches
1	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214	13	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214
2	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214	14	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214
3	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214	15	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214
4	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214	16	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214
5	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214	17	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214
6	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214	18	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214
7	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214	19	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214
8	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214	20	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214
9	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214	21	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214
10	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214	22	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214
11	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214	23	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214
12	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214	24	12,26,43,82,118,131,133, 160,168,202,203,208,212, 213,214

APPENDIX

In order to show efficiency of the proposed formulation for reconfiguration of distribution systems with variable load amounts, the MICP was implemented for summer daily load profile (containing 24 hours) of a practical power system known as Regional Electric Company of Tehran (RECT) [114]. The results including open switches, daily energy losses (kWh), and computation times were listed in Table 15.

According to Table 15, it can be said that the same configurations proposed for fix load amounts (daily peak load values) in Section IV are suggested for network reconfiguration when daily load profile (hourly load levels) is considered. In this case, the power utility should reconfigure the network every day based on radial topologies presented in Table 15. It shows that the selected configurations mentioned in Section IV are enough efficient for daily reconfiguration of distribution systems. It can be seen that the considering daily peak load amounts instead of hourly load levels is sufficient to determine the best daily network configuration. In order to show the efficiency of selected configurations for every hour, the proposed MICP model was run for each hour and the proposed configurations were presented in Tables 15 to 29. The results confirm that selected configurations are the best for 24 hours in practical systems.

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